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WHICH PEOPLE WITH SPECIFIC LANGUAGE IMPAIRMENT HAVE AUDITORY PROCESSING DEFICITS?

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An influential theory attributes developmental disorders of language and literacy to low-level auditory perceptual difficulties. However, evidence to date has been inconsistent and contradictory. We investigated whether this mixed picture could be explained in terms of heterogeneity in the language-impaired population. In Experiment 1, the behavioural responses of 16 people with specific language impairment (SLI) and 16 control listeners (aged 10 to 19 years) to auditory backward recognition masking (ABRM) stimuli and unmasked tones indicated that a subgroup of people with SLI are less able to discriminate between the frequencies of sounds regardless of their rate of presentation. Further, these people tended to be the younger participants, and were characterised by relatively poor nonword reading. In Experiment 2, the auditory event-related potentials (ERPs) of the same groups to unmasked tones were measured. Listeners with SLI tended to have age-inappropriate waveforms in the N1-P2-N2 region, regardless of their auditory discrimination scores in Experiment 1. Together, these results suggest that SLI may be characterised by immature development of auditory cortex, such that adult-level frequency discrimination performance is attained several years later than normal.

INTRODUCTION

Specific language impairment (SLI) is an unexplained difficulty in acquiring spoken language that affects approximately 3% of the child population (Cantwell & Baker, 1987). Children with SLI are typically slow to pass early developmental language milestones, and often have particular difficulty with early acquisition of phonology and morphosyntax (see Leonard, 1998). Children with SLI are also at high risk for literacy problems (e.g., McArthur, Hogben, Edwards, Heath, & Mengler, 2000).

An influential theory maintains that SLI stems from an inability to process rapidly presented sounds. This impairment, here named a rapid auditory processing deficit, is thought to result in unstable representations of speech sounds (phonemes). This interferes with encoding and producing speech, and ultimately leads to receptive and expressive language problems, as well as literacy difficulties (Tallal, 2000).

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A crucial claim of the theory is that the deficit is not speech specific, and can be demonstrated using nonverbal auditory stimuli. The paradigm used most often to present these stimuli is the Rapid Perception Test, which requires listeners to report the order of pairs of brief high- and low-frequency tones separated by different inter-stimulus intervals (ISIs). Listeners with SLI as a group have been found to need a longer ISI between the two tones to identify their order as accurately as control listeners (Ludlow, Cudahy, Bassich, & Brown, 1983; Tallal, 1976; Tallal & Piercy, 1973a, 1973b; Tallal, Stark, Kallman, & Mellits, 1981).

People with SLI have also been found to perform poorly as a group on other psychophysical paradigms that present rapid nonverbal auditory information. These include tasks that require listeners to report whether two rapidly presented brief tones have the same pitch (Tallal & Piercy, 1973a); to respond quickly to deviant tones presented amongst rapidly presented standard tones (Neville, Coffey, Holcomb, & Tallal, 1993); to track the location of rapidly presented clicks through space (Visto, Cranford, & Scudder, 1996); to detect the presence of a tone followed by a backward mask (Wright, Lombardino, King, Puranik, Leonard, & Merzenich, 1997); and to detect brief gaps in sound bursts (Ludlow et al., 1983).

However, not all experiments have found impaired rapid auditory processing in people with SLI. Bishop, Carlyon, Deeks, and Bishop (1999b) found that children with SLI were as good as control children at detecting a brief tone followed by a masking sound. Similarly, Rosen (1999) reported that 14 children with a “grammar specific” language impairment performed normally on auditory temporal processing tasks that had previously discriminated between SLI and control groups. Helzer, Champlin, and Gillam (1996) found that children with SLI and control listeners had similar mean detection thresholds for brief tones presented in noise, and in 40- and 64-ms gaps in noise. Norrelgen, Lacerda, and Forssberg (2002) found high variability and no mean difference between SLI and control children on a computerised same–different task using brief tone stimuli with variable ISIs. Further, other researchers have found that when children with SLI do poorly on auditory tasks, their problems are not necessarily confined to stimuli that are brief or rapid (Bishop, Bishop, Bright, James, Delaney, & Tallal, 1999a; Lincoln, Dickstein, Courchesne, Elmasian, & Tallal, 1992).

After reviewing this contradictory literature, McArthur and Bishop (2001) suggested that one reason for the discrepant findings could be heterogeneity of the SLI population. They noted that even when significant mean differences are found between the rapid auditory processing scores of SLI and control children, there is overlap between the groups, and the variance of scores is typically greater for the SLI group. This suggests that only some children with SLI have a rapid auditory processing deficit (see also Farmer & Klein, 1995).

There is ample evidence for heterogeneity of SLI, in terms of aetiology (Bishop, 2002), neurobiology (Lane, Foundas, & Leonard, 2001), language profile (Bishop, 1997; Rapin, 1996), and associated literacy problems (Bishop & Adams, 1990). However, there is no agreement about the best method for subclassifying children, and attempts to develop a nosology have been hindered by changes in the patterns of difficulties demonstrated by children with SLI as they develop (Conti-Ramsden & Botting, 1999). Consequently, most studies in this field treat SLI as a single group, and focus on group comparisons. In this paper, we suggest that rather than continuing to do studies that ask whether there are mean differences between the rapid auditory processing of SLI and control groups, it may be more fruitful to consider what distinguishes children with SLI who exhibit poor rapid auditory processing from children with SLI who do not. This was the first aim of Experiment 1.

Another issue raised by McArthur and Bishop (2001) concerns the methods used to assess rapid auditory processing. Most tasks have required listeners to discriminate between sounds that differ along a single dimension such as frequency or intensity (i.e., taxing auditory discrimination) whilst presenting them briefly and/or rapidly (i.e., taxing rapid auditory processing). On tasks such as these, poor scores could result from a rapid auditory processing deficit, an auditory discrimination deficit, or a combination of both. The second aim of Experiment 1 was to test which of these accounted for the poor rapid auditory processing scores of people with SLI.

EXPERIMENT 1

Methods

All methods were approved by the Ethics Committee of the Department of Experimental Psychology at the University of Oxford. Informed consent was obtained from each listener and his or her parent or guardian to participate in the research.

Participants

Sixteen children and young adults with SLI (nine males) were recruited from language development centres and support groups throughout England. Sixteen people with normal spoken language skills (eight males) were recruited as age-matched controls from scout and guide groups, a college, and a high school in Oxfordshire. All participants performed within the average range on a test of nonverbal cognitive ability, had no reported auditory, physiological, or neurological problems, and had good hearing sensitivity for a 750 Hz tone (i.e., were able to detect its presence at 20 dB HL). The subjects with SLI scored more than 1 *SD* below the level expected for their age on at least two of four key spoken language tests (see Psychometric assessment). Control participants scored within the average range on at least three of the four spoken language tests. Statistics are illustrated in Table 1.

The SLI and control groups were well matched for age and nonverbal IQ scores, which extended from the high to the low end of the normal range. There was little overlap between the spoken language scores of the two groups. Nonword reading was not a selection criterion, and there was some overlap between the SLI and control groups. However, as anticipated, the SLI group was significantly worse at nonword reading than the control group overall (see Table 1).

Psychometric assessment

All testing was carried out in the Department of Experimental Psychology at the University of Oxford. People were assessed using standardised tests of nonverbal intelligence, spoken language, and nonword reading competence.

Nonverbal IQ test. Nonverbal cognitive ability was assessed with the Standard Progressive Matrices (Raven, Raven, & Court, 1998), which is composed of five sets of 12 items. For each item, the participant selects one of six patterned "subsections" to complete a large pattern that contains a blank subsection. Performance is expressed as standard scores that have a mean of 100 and a *SD* of 15.

Table 1. *Age, nonverbal IQ, spoken language, and nonword reading of the SLI and control groups*

	SLI (N =16)			*Control (N=16)*			*Comparison*	
	M	*SD*	*Range*	*M*	*SD*	*Range*	*t(30)*	*p*
Age	14.55	2.77	10.08–19.59	14.67	2.77	11.24–19.52	0.13	.90
Nonverbal IQ	93.75	14.06	75–119	97.00	11.81	75–113	0.71	.48
BPVS	79.38	15.40	56–110	108.75	7.50	90–128	6.29	<.001*
Figurative language	4.63	1.75	3–9	10.93	2.71	7–16	7.75	<.001*
Recreating sentences	4.56	2.10	3–10	7.94	1.84	6–12	4.84	<.001*
Recalling sentences	4.81	1.64	3–8	10.56	2.37	6–15	7.90	<.001*
Nonword reading	81.31	15.72	60–114	102.44	8.25	87–114	4.76	<.001*

* $p < .05$.

Language tests. Spoken language abilities were assessed with four standardised language tests that are widely used in the United Kingdom. In the British Picture Vocabulary Scale (BPVS; Long Form; Dunn, Dunn, Whetton, & Pintilie, 1982) the participant has to indicate which of four pictures match a word read aloud by the experimenter. Scores are expressed as standard scores with a mean of 100 and *SD* of 15. Recalling Sentences is a subtest of the Clinical Evaluation of Language Fundamentals-Revised (Semel, Wiig, & Secord, 1987) that comprises 26 sentences of increasing difficulty that the participant repeats after the examiner. Standard scores have a mean of 10 and *SD* of 3. Recreating Sentences and Figurative Language are subtests of the Test of Language Competence-Expanded Edition (Wiig & Secord, 1989). Recreating Sentences is composed of 13 items that present a picture and three printed words. The task is to create a sentence that is relevant to the picture and contains the three words in any order. Figurative Language is composed of 12 two-part items. In the first part, the participant is asked to interpret a situation that has been described by the experimenter. In the second part, the participant selects one of four written expressions that best reflects the meaning of the same situation. Scores on these tests are expressed as standard scores that have a mean of 10 and *SD* of 3.

Nonword reading test. Literacy was assessed with a nonword reading test, which is a sensitive indicator of dyslexic-type problems in letter–sound conversion (Bishop, 1991). We used the Martin and Pratt Nonword Reading Test (Martin & Pratt, 1999) that is composed of 54 increasingly difficult nonwords that the participant reads aloud until they make 8 consecutive incorrect responses. Scores are expressed as standard scores with a mean of 100 and *SD* of 15.

Auditory assessment

Rapid auditory processing was tested in four auditory backward recognition masking (ABRM) conditions. Auditory discrimination was tested in an unmasked frequency discrimination (FD) condition. Each listener completed the FD condition first, followed by the four ABRM conditions in random order. All five conditions were composed of 10 practice trials presented through speakers, and 60 experimental trials presented diotically through headphones that attenuated background sound by 30 dB SPL.

FD condition. Trials comprised two tones that were separated by a 500-ms silence. Each tone was visually represented on the PC monitor by a square button (marked "1" for the first tone and "2" for the second tone) that flashed when the tone was played. One tone was 80 dB SPL, 25 ms (including 2.5 ms onset and offset) long, and had a frequency of 600 Hz; the other tone was the same except that it had a higher frequency. The listener's task was to identify the higher tone. A correct response was rewarded by a coloured "thumbs-up" sign on the monitor while an incorrect response prompted an uninteresting black cross.

The frequency of the higher tone was adjusted over 60 trials using a one-up, three-down adaptive procedure (Shelton & Scarrow, 1984) to the level where the listener identified the correct interval 79% of the time. The frequency of the higher tone was initially set at 700 Hz (the ceiling value was 800 Hz) and was adjusted in 25-Hz steps. These were reduced to 5 Hz after the first four reversals in response adjustment. The threshold for each condition was the mean frequency of the higher tone calculated from the last even number of step-size reversals after the first four reversals in response adjustment. A threshold score was accepted if the listener's performance was stable (i.e., fluctuated only slightly around the threshold point) after the fourth reversal in response adjustment. Higher threshold scores represented poorer frequency discrimination.

ABRM conditions. The ABRM conditions used the same stimuli as Winkler, Reinikainen, and Näätänen (1993), who found that significant increases in recognition performance with ISI were associated with significant increases in the size of the mismatch negativity event-related potential (ERP). In this experiment, Winkler et al.'s stimuli were presented using the same procedures as the

FD condition. That is, each ABRM trial presented the same tones as the FD trials, each of which were followed by an 80 dB SPL, 55-ms (including 2.5 ms onset and offset), 1000-Hz masking tone after a silent ISI that was fixed within each ABRM condition (20 ms in ABRM20, 50 ms in ABRM50, 150 ms in ABRM150, and 300 ms in ABRM300). The onset of an auditory backward mask interrupts the processing of a preceding sound's features (in this case the 25-ms tone; Massaro & Burke, 1991). Thus, listeners with slow rapid auditory processing should perform particularly poorly (i.e., have higher threshold scores) in ABRM conditions that only allow a short amount of processing time for the tone (i.e., use a short ISI) before the arrival of the mask (i.e., in ABRM20 and ABRM50) compared to ABRM conditions that allow for a longer amount of processing time for the tone (i.e., ABRM150 and ABRM300).

Results

Group differences

Means and 95% confidence intervals of the FD and ABRM scores of the SLI and control groups are illustrated in Figure 1. There is one missing FD score in the SLI group due to equipment failure. The (invalid) ABRM scores of two listeners with SLI with very high FD thresholds were not included in the analysis because the presence of the backward masks made the task too hard for them (i.e., they performed at ceiling). Between- and within-group differences were tested with two-tailed independent-samples t-tests and repeated measures ANOVAs respectively, with an alpha level of .05.

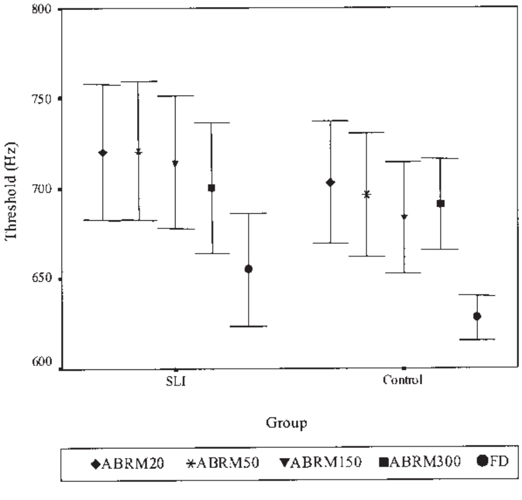

Figure 1. *Means and 95% confidence intervals of the FD and ABRM scores of the SLI and control groups.*

The FD threshold was significantly lower than the ABRM thresholds in both the SLI, ABRM20: $t(12) = 4.06$, $p = .002$; ABRM50: $t(12) = 3.74$, $p = .003$; ABRM150: $t(12) = 4.12$, $p = .001$; ABRM300: $t(12) = 4.27$, $p = .001$, and control groups, ABRM20: $t(15) = 4.92$, $p = .000$; ABRM50: $t(15) = 4.50$, $p = .000$; ABRM150: $t(15) = 4.05$, $p = .001$; ABRM300: $t(15) = 5.22$, $p = .000$. Thus, adding a backward mask significantly increased the pressure on rapid auditory processing for both SLI and control groups (i.e., increased their thresholds), even when there was a silent gap as long as 300 ms separating the tone and the mask. Mean ABRM thresholds generally increased with decreasing ISI in each group. Furthermore, the variance of ABRM scores was large in both groups, and the effect of ISI was not statistically significant, SLI: $F(3, 39) = 0.98$, $p = .41$; controls: $F(3, 45) = 1.65$, $p = .19$.

The mean FD score of the SLI group ($M = 672.67$) was significantly higher than that of the control group ($M = 627.62$); $t(16.98) = 2.44$, $p = .03$; equal variances not assumed. As is typical in this area of research (see McArthur & Bishop, 2001), the mean standard deviation of the SLI group's FD scores ($M = 68.01$) was also significantly higher than that in the control group ($M = 22.99$); $F(1, 29) = 20.31$, $p < .001$. The stem-and-leaf plot in Figure 2 indicates that these effects were due to five people with SLI who had very poor FD scores. The remaining 10 listeners with SLI had normal FD scores.

None of the differences between the mean ABRM thresholds of the SLI and control groups were statistically significant. However, as noted above, ABRM scores are the product of rapid auditory processing and auditory discrimination (in this case, FD). This is supported by the moderate-

Frequency Discrimination Thresholds
Leaf Unit = 1 Hz

Control		SLI
	800	
	700	86 94
	700	74
	700	
	700	28
	700	13
82	**600**	
77	**600**	62
42 40	**600**	48 50
31 29 24 21	**600**	22 28 39
16 15 15 13 11 10 10 05	**600**	08 09 10 18
16	***N***	15
627.62	***M***	672.67
22.99	***SD***	68.01

M: $t(16.98) = 2.44, p = .03$
(equal variance not assumed)
SD: $F(1, 29) = 20.31, p = <.001$

Figure 2. *Stem-and-leaf plots (see Tukey, 1997) and statistics of the FD scores of the SLI and control groups.*

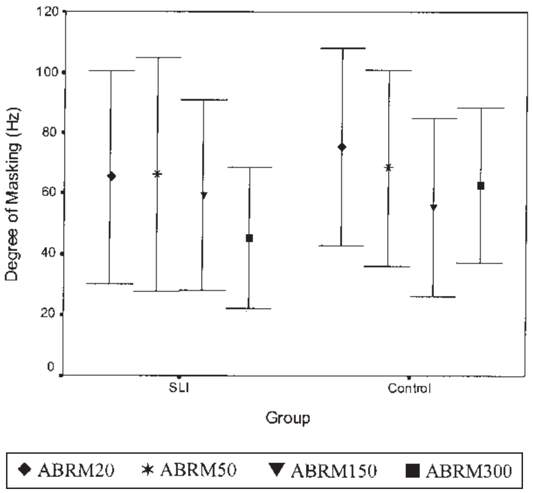

Figure 3. *Means and 95% confidence intervals of the degree of masking experienced by the SLI and control groups.*

to-strong correlation coefficients between listener's FD thresholds and their ABRM20 thresholds (r = .42, p = .02), ABRM50 thresholds (r = .39, p = .04), ABRM150 thresholds (r = .50, p = .005), and ABRM20 thresholds (r = .58, p = .001): Note; these would be even higher if they included the (invalid) scores of the two SLI listeners whose FD thresholds were so high that they performed at ceiling in the ABRM conditions.

To obtain a measure of rapid auditory processing independent of FD, the FD threshold of each listener was subtracted from their ABRM threshold. The result reflects degree of masking: That is, how much a person's frequency discrimination is impaired by the presence of the masking tone. The degree of masking experienced by the listeners with SLI and controls in each ABRM condition are illustrated in Figure 3.

Data were analysed using a repeated measures ANOVA, with group as a between-subjects factor and ISI as the repeated measure. The degree of masking generally increased with decreases in ISI for both groups. However, there was no significant effect of ISI, $F(3, 81) = 1.65$, $p = .18$, or group, $F(1, 27) = 0.13$, $p = .72$, and the interaction between group and ISI was not significant, $F(3, 81) = 0.60$, $p = .62$. It appeared that the amount of variance in the backward masking thresholds of our listeners obscured the observable effect of ISI on thresholds, which Winkler et al. (1993) had found to be statistically significant in normal adults.

In sum, when we used a measure of degree of masking that controlled for baseline frequency discrimination, there was no hint of a difference between the SLI and control groups. However, on the unmasked frequency discrimination task, there was a significant group difference, which was due to five people with SLI who had poor frequency discrimination thresholds.

Individual differences

What differentiated the listeners with SLI with poor FD scores from those who had normal FD thresholds? We computed Pearson correlation coefficients between FD scores and (1) age, (2) spoken language scores, and (3) nonword scores in the SLI group (see Table 2). We have not

Table 2. *Pearson R and partial correlation coefficients (adjusted for age) between frequency discrimination, age, nonword reading, nonverbal IQ, and spoken language in the SLI group*

	Age	*Nonword reading*	*Nonverbal IQ*	*BPVS*	*Figurative language*	*Recreating sentences*	*Recalling sentences*
r	−.50	−.63*	.08	.07	−.02	−.41	.07
p	.06	.01	.79	.08	.95	.13	.80
N	15	15	15	15	15	15	15
partial *r*	–	−.82*	−.17	−.29	−.08	−.57*	−.09
p	–	.00	.55	.32	.78	.04	.76
df	–	12	12	12	12	12	12

* $p < .05$.

presented the same coefficients for the SLI and control groups combined because the groups were preselected for poor (SLI group) and normal scores (control group) on the same spoken language tests, which could artificially inflate the relationships between the spoken language and FD scores.

All the variables were normally distributed in the SLI group. There was a strong association between FD and nonword reading scores in the SLI group. There was a moderate association between FD scores and age, but no association between FD scores and nonverbal IQ scores. Accordingly, partial correlation coefficients accounting for age were calculated between the same variables (Table 2). These revealed an even stronger association between FD and nonword reading scores in the SLI group. There was also a moderate association between FD and scores on the Recreating Sentences subtest. To test the possibility that this arose because the task involved reading the test words, we partialled out the effect of nonword reading from the relationship. The partial correlation coefficient was much lower ($r = -.12$, $p = .71$), indicating that the relationship between FD and the Recreating Sentences score was driven by the strong association between FD thresholds and reading ability.

The association between FD thresholds and age in the SLI group was potentially interesting because FD thresholds are known to improve throughout childhood. However, age did not appear to account for the poor FD thresholds for two reasons. First, all the listeners in the SLI-poor FD group were older than 7 years. Two were older than 12 years, which is when FD thresholds should be at adult levels (Maxon & Hochberg, 1982; Thompson, Cranford, & Hoyer, 1999). Second, the SLI-normal FD and control groups had listeners who were the same age as the SLI-poor FD group (i.e., 10, 11, 13, 14, and 16 years) and who produced normal FD thresholds, so younger listeners did not necessarily produce poor FD thresholds. Thus, even though the difference between the mean age of the SLI-poor FD and SLI-control FD groups was statistically significant—SLI-poor FD: $M = 12.25$ years, $SD = 1.89$; SLI-normal FD: $M = 15.51$ years, $SD = 2.63$); $t(13) = 2.46$, $p = .03$—age alone did not explain the poorer FD scores of the SLI-poor FD group.

Discussion

The aims of Experiment 1 were to investigate what differentiated people with SLI with poor rapid auditory processing from people with SLI who had normal auditory processing, and to determine whether their true deficit lay with rapid auditory processing, auditory discrimination, or a combination of both. There was no hint of a difference between SLI and control groups in degree of masking in the ABRM conditions, indicating that people with SLI were not poorer at rapid auditory processing than controls. However, a subgroup of people with SLI did perform poorly relative to controls in the FD condition. The strong negative correlation coefficients between the FD and nonword reading scores in the SLI group indicated that the people with SLI who had poor FD scores had relatively poor nonword reading. They also tended to be younger than the rest of the SLI sample.

Our results raise questions about the type of auditory processing deficit that these people have. The results of this experiment suggest that rather than having a problem with processing rapidly presented sounds, these people are less able to discriminate between the frequencies of nonverbal sounds regardless of their rate of presentation. This finding is congruent with a growing number of experiments that have found a similar group of people—people with a specific reading disability (commonly known as dyslexia)—performing poorly on tasks that tax frequency discrimination of pure tones (Ahissar, Protopapas, Reid, & Merzenich, 2000; Baldeweg, Richardson, Watkins, Foale, & Gruzelier, 1999; Cacace, McFarland, Ouimet, Schreiber, & Marro, 2000; Hari, Sääskilahti, Helenius, & Uutela, 1999; McAnally & Stein, 1996); complex nonspeech sounds (Temple et al., 2000); frequency-modulated tones (Hill, Bailey, Griffiths, & Snowling, 1999; Stein & McAnally, 1995; Witton et al., 1998, though cf. Bishop, et al., 1999b); and dichotic pitch perception (Dougherty, Cynader, Bjornson, Edgell, & Giaschi, 1998). This finding is particularly compatible with Hill et al.'s (1999) finding that only a subgroup of adult poor readers have impaired frequency discrimination for pure tones.

Thus, the poor performance of some people with SLI on rapid auditory processing tasks may stem from a lesser ability to discriminate between the frequency of sounds rather than to process rapidly presented sounds. However, this evidence is based solely on performance on psychophysical tasks. Scores on such tasks may be influenced by nonperceptual factors such as attention and motivation as well as perceptual acuity (Gomes, Sussman, Ritter, Kurtzberg, Cowan, & Vaughan, 1999; Kallman & Massaro, 1979; Winkler & Näätänen, 1992). Further, the two-interval forced-choice task used in Experiment 1 required listeners not only to discriminate a difference between two tones, but also to identify the interval that contained the higher test tone. Poor performance on this task could result from a deficit in a higher-level task-related process such as stimulus categorisation as well as a lower-level auditory perceptual deficit (Marshall, Snowling, & Bailey, 2001). In Experiment 2, we asked whether a similar pattern of auditory deficit could be demonstrated with these participants using a measure that does not rely on overt behavioural responses.

EXPERIMENT 2

Auditory ERP components provide a method for assessing the integrity and speed of operation of cortical processes underlying auditory perception. The auditory ERP is obtained by averaging tiny electrical responses that can be recorded from electrodes placed on the scalp as the participant listens to auditory stimuli. When responses to large numbers of stimuli are averaged, random noise in the signal is averaged out, and a distinct waveform becomes apparent, as shown in Figure 4. The first negative peak that occurs 100 to 150 ms after the onset of a sound is called the N1. The following positive peak at 150 to 200 ms is called the P2.

Several researchers have noted the potential value of the N1-P2 complex for assessing low-level auditory perceptual processing in children with language impairments, but results have been mixed. Mason and Mellor (1984) recorded responses to a 200-ms, 1000-Hz tone burst and found no differences in either latency or amplitude of N1-P2 in language-impaired compared to control children,

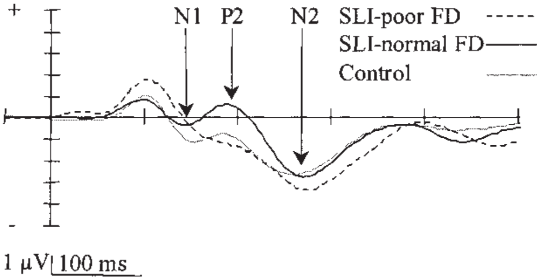

Figure 4. *Mean auditory ERP responses of the SLI-poor FD group, the SLI-normal FD group, and control group. Positive activity is plotted upwards.*

although there was evidence of abnormal lateralisation of the ERP suggestive of left hemisphere dysfunction. Adams, Courchesne, Elmasian, and Lincoln (1987) found a larger P2 in language-impaired compared with control children, but they only had five children in each group. Lincoln, Courchesne, Harms, and Allen (1995) found abnormally large N1 amplitudes and latencies in a group of people with children with SLI (but no difference for P2 amplitude) in their second experiment. And Tonnquist-Uhlen (1996) found that a group of children with SLI had a significantly smaller and later mean P2 component than control children. This small group of ERP studies indicate even more discrepancies and uncertainty in findings than are seen with behavioural data.

However, the reason for the inconsistencies in the ERP studies may be the same as the reason for the mixed findings in the behavioural experiments: Neville et al. (1993) concluded from their ERP study that multiple factors may cause language impairments, and we need to develop methods for identifying subtypes associated with different underlying problems. The study of Neville et al. was unusual in that they obtained behavioural and neurophysiological data from the same children. When they compared their SLI group with controls, they found no difference in auditory ERPs (although, intriguingly, group differences were seen on visual ERPs). However, they then subdivided their sample according to performance on a test of rapid auditory processing, and found that children who did poorly had unusually small and late N1 responses measured from right frontal sites.

Another factor to consider when conducting ERP studies with children is that auditory ERPs continue to show developmental changes into adolescence (Ponton, Eggermont, Kwong, & Don, 2000). In line with other researchers (Courchesne, 1990; Ponton et al., 2000), we have found that pre-adolescent children do not always show an N1-P2 complex at midline electrodes, and when it could be measured, the N1 became larger and earlier with age (McArthur & Bishop, 2002). Thus, it is important to take age into account when comparing ERPs of clinical and control groups.

In Experiment 2, we measured the N1-P2-N2 complex in children as they were presented with the same tone used in the FD condition in Experiment 1. Our aim was to consider how performance on the FD task related to N1-P2-N2 components that were passively evoked when the participant's attention was directed elsewhere.

Method

The same 16 people with SLI and 16 control listeners returned to complete the second experiment. Two of four blocks of 250 stimuli used a 25-ms, 80-dB SPL, 600-Hz tone as a standard stimulus (85% of trials) and a 25-ms, 80-dB SPL, 700-Hz test tone as a deviant stimulus (15% of trials), and the other two blocks used the reverse (deviant stimuli were presented to calculate the mismatch negativity, MMN, which is not considered here because we subsequently found that the reliability of the MMN is significantly lowered when an EEG is recorded with the video sound left on; McArthur & Bishop, 2003). The blocks were presented in random order. The gap between each trial was jittered randomly from 320 and 420 ms to avoid anticipatory ERP artefacts.

Participants were seated in a comfortable lounge chair in an electrically shielded testing booth. They listened to the FD stimuli diotically through headphones while they watched a self-selected video on a small television 1.3 m away. The video's soundtrack was played at a low level (approximately 50 dB SPL) to better divert the listener's attention away from the experimental stimuli. We have found that a video soundtrack at low volume has negligible effect on the reliability of the auditory ERP of adults.

The EEG was recorded from nonpolarised tin electrodes positioned according to the 10-20 International system: three midline sites (FPz, Fz, FCz,) and five sites over each hemisphere (F1/F2, F3/F4, F7/F8, FC3/FC4, FT7/FT8). The ground electrode was positioned on the midline between FPz and Fz. The right mastoid was used as the online reference electrode. The vertical electro-oculargram (VEOG) was recorded from above and below the right eye; the horizontal electro-oculargram

(HEOG) was recorded 1 cm from the outside of the outer canthi of each eye. The signal was amplified 20,000 times and sampled at 250 Hz (i.e., once every 4 ms).

Each participant's EEG was processed offline. The scalp recordings were referenced to the mean activity of the left and right mastoids. The influence of VEOG activity was removed from the EEG sites (ocular artefact reduction) using an algorithm of an average "blink" that was calculated from at least 20 VEOG epochs of 400 ms that were triggered by a 10% increase in VEOG activity (Neurosoft, Inc., 1999). The EEG activity was then band-pass filtered with a 10-Hz low-pass filter (12 dB-per-octave roll-off) and a 0.1-Hz high-pass filter (same roll-off). The EEG was divided into 550-ms epochs with a 50-ms pre-stimulus interval. Epochs were baseline corrected from −50 to 0 ms. Epochs with changes in HEOG or EEG activity greater than 150 μV were rejected.

The auditory ERP of each listener was calculated by averaging epochs of all standard stimuli (600 Hz and 700 Hz) excluding those that fell immediately after a deviant stimulus. Activity at Fz was used to represent the auditory ERP as it recorded the largest response, it is the site most commonly used to represent auditory ERPs, and because it is one of the few sites where analogous N1 and P2 responses can be measured in adults and children older than 9 years (Ponton et al., 2000). N1 was the first negative peak in the auditory ERP that fell between 100 and 200 ms (see Figure 4). P2 was the second positive peak that occurred between 150 and 250 ms. N2 was the second negative peak that fell between 200 and 300 ms. The N1-P2-N2 complex was represented by the pattern of activity between 128 and 256 ms post-stimulus onset (see below and Figure 5 for details). We did not represent N1, P2, or N2 using more traditional peak or mean amplitude measures because these measures provide invalid data when the components are missing. Specifically, if N1 and P2 are missing, activity increases in negativity in a near-linear way from P1 down to N2 (see Figure 5). If N1 or P2 are measured as the largest negative or positive peaks (respectively) within a specified interval, they would simply receive the value of the lowermost point (N1) or uppermost point (P2) of the line in that interval. Ironically, this often produces particularly large N1 and P2 measures, even though these components are missing entirely.

Results

The first consideration was whether there was a difference between the number of epochs rejected due to artefact in the groups. The difference between the mean number of accepted trials averaged together for the auditory ERP responses in the SLI-poor FD group ($M = 676.4$, $SD = 22.0$), the SLI-normal FD group ($M = 687.0$, $SD = 13.14$), and the control group ($M = 689.5$, $SD = 9.14$) was not statistically significant, $F(2, 28) = 1.94$, $p = .16$.

The second consideration was the reliability of the waveforms, which we tested by calculating the intra-class correlation coefficient between each listener's mean ERP response to 600-Hz tones and their mean ERP response to 700-Hz tones (split-half reliability). Intra-class correlation coefficients measure how similar two waveforms are in their shape and absolute voltage. For each child we computed a coefficient that could range from 0 (completely different) to 1.0 (the same) to −1.0 (the opposite); $(2N.\Sigma XY - (\Sigma X + \Sigma Y)^2)/(N.(\Sigma X^2 + \Sigma Y^2) - (\Sigma X + \Sigma Y)^2)$, where X is the value from the first waveform, Y is the value from the comparison waveform, and N is the total number of observations (i.e., 2 times the number of data points in each waveform). The difference between the split-half correlation coefficients of the SLI-poor FD group ($M = 0.51$, $SD = 0.36$), the SLI-normal FD group ($M = 0.32$, $SD = 0.59$), and the control group, ($M = 0.41$, $SD = 0.44$) was not statistically significant, $F(2, 28) = 0.26$, $p = .78$.

The mean auditory ERP responses of the SLI-poor FD group, the SLI-normal FD, and the control group are compared in Figure 4. The N1 and P2 components were strikingly absent in the SLI-poor FD group (broken black line) compared to the other two groups. However, as noted above, the SLI-poor FD group were significantly younger than other participants with SLI. We know that the likelihood of finding N1-P2 is lower in younger children (McArthur & Bishop, 2002; Ponton et al., 2000). If

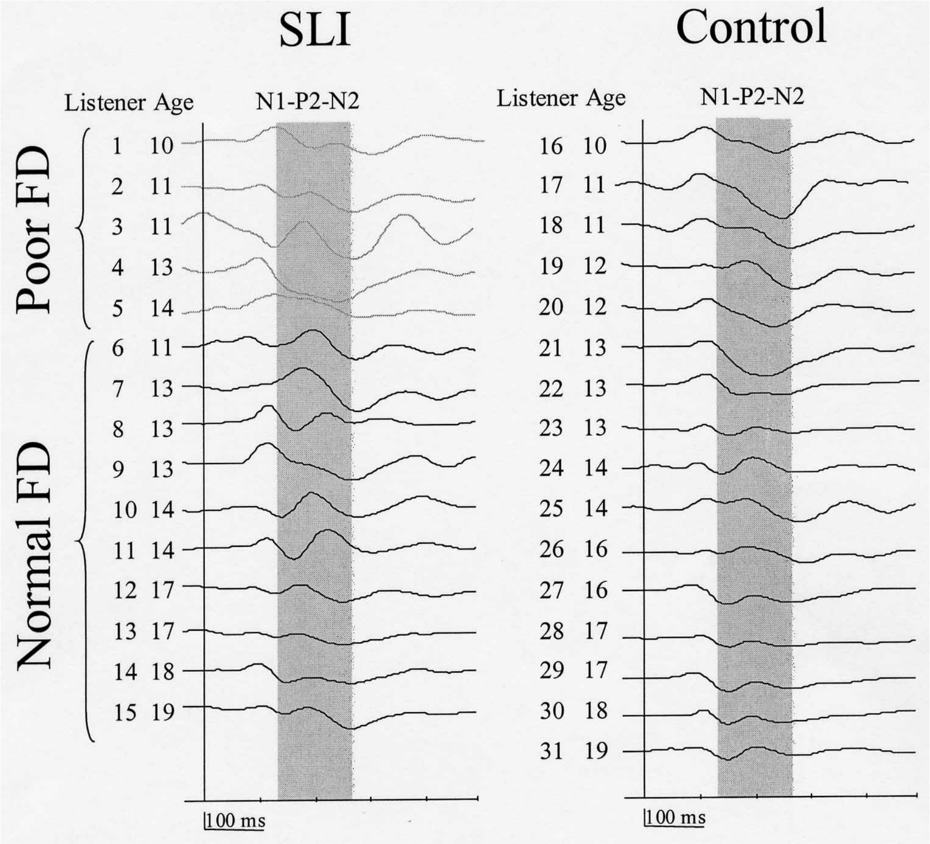

Figure 5. *Individual auditory ERPs of the SLI-poor FD (1 to 5), SLI-normal FD (6 to 15) and control listeners (16 to 31). Positive activity is plotted upwards.*

we subdivide the control group by age, with a cutoff at 14 years, we find that all eight children in the older group show N1-P2, whereas four of the eight younger children do not. This raises the question of whether the lack of N1-P2 in the SLI-poor FD group is simply a consequence of their age.

We examined this issue in two ways: visual inspection of ERPs and a statistical analysis. The individual auditory ERPs of the SLI-poor FD, SLI-normal FD, and control groups are shown in Figure 5. The SLI group is missing the ERP response of the listener who did not have a FD threshold score due to equipment failure, and therefore could not be classified as having poor or normal FD.

For the visual analysis, we asked two colleagues, who do not do ERP research, to blindly rank how similar each listener's ERP was to their age-appropriate ERP in the N1-P2-N2 region (128 to 256 ms). Rankings ranged from 1 (best match) to 31 (worst match). The two rankings were well matched ($r = .88$; $p < .001$), so we averaged the two ranks for each listener. There was a significant group difference between the mean rankings of the SLI-poor FD group ($M = 23.90$, $SD = 6.85$), SLI-normal FD group ($M = 20.15$, $SD = 7.50$), and the control group ($M = 10.94$, $SD = 7.02$); $F(2, 28) = 8.73$, $p = .001$. This was due to the significantly higher mean ranking of the control group compared to the SLI-poor FD and SLI-normal FD groups ($p = .006$ and .01 on a Scheffe test, respectively), which did not differ from each other ($p = .64$). Thus, both the SLI-poor FD and SLI-normal FD groups appeared to have abnormal N1-P2-N2 responses for their age compared to the control group.

To obtain a quantitative measure of how normal the N1-P2-N2 responses of the SLI-poor FD and SLI-normal FD groups were for their age, we divided the control group into two, and created an average "standard" ERP response for normal listeners younger than 14 (young standard ERP) and an average "standard" ERP response for normal listeners older than 14 (older standard ERP). We then calculated the intra-class correlation coefficient between each SLI listener's ERP response in the N1-P2-N2 region (i.e., 128 to 256 ms; see shaded area in Figure 5) and the appropriate "standard" ERP response in the N1-P2-N2 region for their age. This procedure is analogous to comparing a child's reading test score to the mean test score of children the same age to determine whether their reading is age appropriate. In this case, the higher the coefficient, the more appropriate the SLI listener's N1-P2-N2 response for their age.

A potential problem with this procedure is that the average ERP for the younger controls could be an average with very substantial variation around it. So, each control contributing to that average might be just as discrepant from the average as the SLI-poor FD group. To test this, we compared the ERP of each control to the mean ERP of the remaining controls in their appropriate age-range (i.e., above or below 14 years). If the ERPs of younger controls did vary as much from the age-appropriate mean ERP as the SLI-poor FD group, then there would be no difference between the intra-class correlation coefficients of the SLI-poor FD group and the control group in the N1-P2-N2 region.

The mean intra-class correlation coefficients of the SLI-poor FD group ($M = -0.02$, $SD = 0.49$) and the SLI-normal FD group ($M = -0.04$, $SD = 0.37$) were similarly low compared to the control group ($M = 0.26$, $SD = 0.39$). Merging the coefficients of the two SLI groups together, there was significant group difference between the mean intra-class coefficients of the SLI ($M = -0.03$, $SD = 0.40$) and control groups, $t(29) = 2.11$, $p = .04$. Thus, the statistical analysis and the visual analysis indicated that both the SLI-poor FD group and the SLI-normal FD group had abnormal N1-P2-N2 responses for their age compared to controls.

Discussion

We had anticipated one of two outcomes from Experiment 2: Either the SLI-poor FD group would have abnormal auditory ERPs and the SLI-normal FD group would have normal ERPs, or both SLI groups would resemble normal controls. In fact, we found that *both* SLI subgroups had age-inappropriate ERPs in the N1-P2-N2 range compared to the controls, regardless of their FD thresholds. This unexpected result suggests that auditory processing may be deficient in the majority of cases of SLI, but that the FD task that we used may be insufficiently sensitive to detect this in all individuals. This could be the case if there were delayed maturation of auditory cortex in SLI. Recent neurophysiological data indicate a prolonged developmental course of maturation for auditory systems, continuing well into adolescence (Ponton et al., 2000). Suppose this process were delayed by an average of around 4 years in SLI, and that the level of neurophysiological maturity determined frequency discrimination performance. We know that adult levels of auditory frequency discrimination are not achieved until 8 years or more in most typically-developing children (Thompson et al., 1999). Thus, children with SLI who were aged 10 or 11 years would resemble typically-developing 6- to 7-year-olds, and have elevated thresholds. In contrast, people with SLI aged 14 or 15 would resemble typically-developing 10- to 11-year-olds, and score close to adult levels on a frequency discrimination task. Our ERP data suggest that the good performance of older listeners with SLI does not mean that their auditory neurodevelopment has completely caught up with their peer group. Rather, it has reached a level that is sufficient to mediate adequate frequency discrimination. Two predictions follow from this interpretation. First, if we used a more taxing auditory task that differentiates typically-developing adolescents from adults, then we should see deficits in adolescents with SLI compared with age-matched controls. Second, if we follow up individuals with SLI as they grow older, their ERPs should show a normal, but delayed course of development.

The underlying neurophysiological basis of maturational changes in the ERP can only be speculative until further research identifies the source of the N1-P2-N2 complex. Relatively little is known about these components. The N1 is thought to reflect activity of several independent generators, originating in the primary auditory cortex, the postero-superior temporal plane, and nonspecific frontal areas (Bruneau & Gomot, 1998). P2 is supposed to be generated by at least two locations in the supratemporal auditory cortex (Näätänen, 1992; Tonnquist-Uhlen, 1996) or in the mesencephalic reticular activating system (Ponton et al., 2000). So, the abnormal N1-P2-N2 responses of people with SLI may reflect impaired "processing" in the supra-temporal and frontal regions of the brain. More work is needed to establish whether this processing is related to neural transmission speed (Sharma, Kraus, McGee, & Nicol, 1997), the triggering of attention (Hyde, 1997; Neville et al., 1993), the "tuning" of the auditory processing system (Leppanen & Lyytinen, 1997), or number of pyramidal cell synapses (Ponton et al., 2000).

CONCLUSIONS

Four conclusions stem from this study. First, most research on auditory deficits in SLI has focused on rapid auditory processing, with little attention to frequency discrimination. The current study suggests that some people with SLI have difficulty with behavioural tasks that require them to distinguish sounds of different frequency even when sounds are not presented rapidly (see also Lincoln et al., 1995). Second, Experiment 1 emphasises the importance of examining individual differences as well as group means when investigating children with developmental disorders. Where group differences are found, they typically arise because a subset of the SLI group shows impairment, while the remainder score in the same range as controls. Third, we need to identify the characteristics of those children who do have deficits. In this study, there were two factors that characterised the cases with poor frequency discrimination: They tended to be younger than other cases of SLI, and they had particularly poor performance on a test of nonword reading. Fourth, although the latter result might seem to imply there is a distinct subtype of SLI with combined auditory, language, and literacy problems, our ERP data suggested a maturational explanation. Regardless of their auditory frequency discrimination performance, people with SLI tended to have age-inappropriate ERPs. We suggest that maturational status may be a key factor determining how SLI presents, and that ERP data can provide a sensitive indicator of underlying neuro-developmental immaturity.

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