Auditory Temporal Resolution in Children with Specific Language Impairment

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There are controversies surrounding the issue of temporal auditory processing and specific language impairment (SLI). This article explores the influence of tone frequency on temporal resolution in SLI. The Auditory Fusion Test-Revised (AFT-R) was carried out with 19 children with SLI and 19 control children with normal language development. No between-groups differences in temporal resolution were found for 0.25 and 1 kHz tones, but the SLI group showed poorer temporal resolution at 4 kHz. No relationship was noted between temporal resolution and measures of nonverbal intelligence and language measures. Two subgroups of SLI, one with poor and the other with good temporal resolution, were identified. The SLI subgroup with poor temporal resolution had better frequency discrimination than the SLI subgroup with better temporal resolution. This inverse relationship, not reported before in SLI, can be due to right hemispheric dominance in SLI. However, other possibilities can exist, and it may be speculated that the impaired temporal resolution in a subgroup of SLI is linked more to central neural timing mechanisms than to auditory processing relevant for speech and language development.

Specific language impairment (SLI) has been defined as a persistent developmental limitation in language development in the absence of obvious explanatory factors such as severe hearing loss or severe cognitive dysfunction (Leonard, 1998). Tallal (2000) reviews the evidence for impaired abilities of SLI children in "processing brief, rapidly successive acoustic cues" in nonverbal and verbal stimuli, and characterizes SLI as "a pervasive rate processing constraint that particularly affects the development of normal phonological processing and grammatical morphology, leading to both oral and in many cases written language deficits" (Tallal 2000, p. 150). Leonard (1998) recognizes the difficulty in processing brief or rapidly presented stimuli as an important piece of the SLI puzzle but suggests a number of other pieces to the SLI puzzle, with various forms of constrains in information processing that may be either specific or generalized. Controversy remains as to the explanation for the significant disruption in language development, and this is exaggerated by experimental variations among research groups producing results that conflict with Tallal's influential theory of impaired auditory temporal processing, with some studies failing to show that impaired auditory temporal processing is associated with SLI (Bishop, Carlyon et al., 1999; Helzer et al., 1996; McArthur & Bishop, 2004; Norrelgen et al., 2002). Some authorities have claimed "auditory temporal processing is neither necessary

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nor sufficient for causing language impairment in children" (Bishop, Carlyon, et al., 1999).

Various reasons for these disparate results have been cited, including differing selection criteria, stimulus design, methodology, demands on attention, and problems related to psychophysical tasks (McArthur & Bishop, 2001; Tallal, 2000, p. 142). Poor discrimination ability, for different frequencies and intensities, is seen as a possible stimulus design-related factor (McArthur & Bishop, 2001) that may result in some SLI subjects performing less well in tasks with brief rapidly presenting stimuli. Tallal's Auditory Repetition Test (ART) used two different tones and, hence, the confounding effect of poor frequency discrimination on temporal resolution could not be ruled out. These psychophysical tasks involved sequencing of sounds and pressing panels and, therefore, effects of task-related complexities on the auditory performance of SLI children could not be ruled out either. The effect of task-related complexity on auditory performance of SLI children was clearly demonstrated by Riddle (1992), and Leonard (1998, p. 143) also stressed this point after a thorough review of the literature.

Effects of individual frequencies per se on auditory temporal processing in SLI have also not been investigated to any great extent. Table 1 shows

TABLE 1. Frequencies and methods used for assessing auditory processing in children with SLI.

Publications	Sound Frequencies Used	Auditory Processing Deficit	Type of Test
Lowe & Campbell, 1965	High 2200 Hz Low 400 Hz	Yes	JOISI
Tallal & Piercy, 1973	High 180 Hz Low 54 Hz	Yes	JOISI
Tallal & Piercy, 1973	High 180 Hz Low 54 Hz	Yes	SDT
Robin et al., 1989	440 Hz	Yes	JOSP
Neville et al., 1993	Target 1000 Hz Standard 2000 Hz	No: Normal ART Yes: Poor ART	Identify Target sounds
Helzer et al., 1996	High 2000 Hz Low 500 Hz	No	DTCNN
Wright et al., 1997	1000 Hz	Yes	ABM
Bishop, Bishop et al., 1999	High 300 Hz Low 100 Hz	No effect of ISI	JOISI
Bishop, Carlyon et al., 1999	1000 Hz	No	ABM
Bishop, Carlyon et al., 1999	1000 Hz	No	FMT
Bishop, Carlyon et al., 1999	Centered on 212 Hz	No	FFD
McArthur & Hogben, 2001	1000 Hz	Yes 41% No 59%	ABM
Norrelgen et al., 2002	High 1350 Hz Low 878 Hz	No	SDT
McArthur & Bishop, 2004	High 700–800 Hz Low 600 Hz	No	ABM
McArthur & Bishop, 2004	High 700–800 Hz Low 600 Hz	Yes 33.3% No 66.6%	FD

Note: **JOISI:** Judgment of order of two tones with varying interstimulus intervals; **SDT:** Same different task to discriminate if two rapidly presented tones are of the same or different pitch; **JOSP:** Judgment of sound patterns (made of six tones of the same frequency and two interstimulus interval); **ART:** Tallal's auditory repetition test; **DTCNN:** Detection of brief tones in masking noise in continuous and notched noise; **ABM:** Auditory backward masking; **FMT:** Discrimination of an unmodulated tone from a frequency modulated tone; **FFD:** Fundamental frequency discrimination without spectral cues; **FD:** Frequency discrimination of tones.

that different methods and frequencies have been used to evaluate many different aspects of auditory processing behaviorally using low- and mid-frequency sounds. There is contradictory evidence as to the relationship between auditory temporal resolution and sound frequency. Some studies (Florentine, 1982; Irwin et al., 1985; Wightman et al., 1989) suggest that temporal processing improves with an increase in sound frequency. These findings were explained by the fact that in normal subjects the temporal resolutions of the low-frequency auditory channels are inherently inferior to those of the high-frequency channels (Shailer & Moore, 1983; Stuart & Phillips, 1998). Other studies, however, failed to show any relationship between temporal resolution and signal frequency in normally developing individuals (Davis & McCroskey, 1980; Green, 1973). The temporal resolution of the low-frequency sounds, at least up to 1000 Hz, is related to the critical bandwidths of the peripheral auditory system in the ear, whereas the temporal processing of higher frequency signals is dependant on more central processes that mature earlier (Shailer & Moore, 1983). There is contradictory evidence from electrophysiological and neuroimaging studies regarding cortical response to low- and high-frequency sounds (Wunderlich & Cone-Wesson, 2000). Evoked potential measurements are not ideal to compare the cortical responses to low- and high-frequency sounds, as topographical differences of the cortical areas processing high- and low-frequency sounds will confound the results, whereas functional imaging is ideal. Lockwood et al. (1999) mapped the brain activation by low- and high-frequency sounds using positron emission tomography (PET) and showed that, in normal subjects, 4 kHz tones activated more areas in the brain compared to 0.5 kHz tones, suggesting the 4 kHz tone would require more processing in the brain. If SLI results from some form of limited processing abilities in the brain, it would, therefore, be logical to suspect that the 4 kHz tone would be more affected in SLI subjects than lower frequency tones.

The question therefore arises as to whether the inconsistencies in the literature regarding impaired temporal processing abilities in SLI result from experiments not using higher frequency sounds, which is apparent from Table 1. Table 1 also shows how auditory temporal processing has been studied in different ways in SLI, with understandably different outcomes. There are issues relating to the term *temporal auditory processing* used in the context of SLI, as it is not clear if this means "rate of perception" or "perception of rate" (Studdert-Kennedy & Mody, 1995). A basic and simple way to measure auditory temporal processing would be to assess the rapidity with which the auditory system functions by measuring temporal resolution. Hirsh and Sherrick (1961) state that it was Exner (1875) who carried out early extensive works on temporal perception of sounds in healthy subjects, using click sounds, and suggested that the minimum time gap between two separate clicks required for them to be perceived as separate sounds is a measure of how rapidly the auditory system can process sounds. If the second click is presented with a very short time gap before the auditory system has processed the first click, the two clicks are perceived as one. When the time gap between two successive sounds are gradually increased, they will be perceived as two separate sounds when the second sound is presented any time after the auditory system had completed processing the first sound. The shortest time gap between two successive sounds at which the two sounds begin to be perceived as separate is the temporal acuity or temporal resolution. Gap detection tasks are considered to be the preferred behavioral measure of auditory temporal processing where the minimum gap for a listener to hear two sounds rather than one is determined (Trehub et al., 1995).

To evaluate the influence of different sound frequencies on the auditory temporal processing in SLI, gap detection tasks with either narrow band noises or pure tones could be used. Amplitude fluctuations associated with narrow band noise can be confused with gaps (Trehub et al., 1995) and therefore are best avoided. Pure tones are not without problems due to spectral splatter, but shaping the tones to avoid sudden onset or offset significantly minimizes the problems. Detecting the gap between two tones of the same frequency also removes any criticism of confounding effect of frequency discrimination on temporal processing in SLI. A search for a gap detection task that met the criteria of frequency specificity without the confounding effect of frequency discrimination, and at the same time avoided any task-related complexities, lead us to the Auditory Fusion Test-Revised (AFT-R; McCrosky & Keith, 1996), a test that is easy to perform and is not demanding from cognitive and linguistic points of view. Children developmentally mature enough to have acquired the concepts of one and two, and the ability to say "one" and "two," will be able to perform this test. The AFT has been used by a number of researchers (Davis & McCrosky, 1980; Isaacs et al., 1982; McCroskey & Kidder, 1980) and has been shown to be a valid test to categorize different clinical groups based on their performance. Normative data exist for children 3 years and older (Keith, 2001; McCroskey & Keith, 1996).

Apart from the stimulus and auditory task-related issues affecting the outcome of auditory temporal processing abilities in children with SLI, the notoriously heterogeneous nature of the group could also result in inconsistent outcomes. Standardized language tests are used to characterize children for experimental purposes, but these characterizations have tended to be patchy in auditory temporal processing studies, providing insufficient detail of language testing for the results to be interpretable as evidence for causality. Studies of auditory processing, therefore, require an accurate and thorough description of the SLI group's language performance based on widely available assessments and taking into account contemporary issues in SLI research. The traditional attempt to define and select children with specific language impairment in otherwise healthy children using a standard approach with specific inclusion and exclusion criteria came from Stark and Tallal (1981). The cognitive and linguistic criteria required a performance IQ score of 85 or above and at least one of the following: age equivalent score in receptive language ability at least 6 months or expressive language ability at least 12 months or combined language ability at least 12 months below the developmental age or the chronological age, whichever is lower. The language score criteria Stark and Tallal (1981) used was based on a battery of four receptive and five expressive language measures, and the test scores were averaged to get composite scores for receptive, expressive and overall language age. There are serious pitfalls in indiscriminate combination of test scores, as the tests are not all equally sensitive (Lahey, 1990; Plante, 1998), and the use of one most accurate test is preferable. Many good researches on SLI are based on various adaptations of the Stark and Tallal (1981) criteria (Plante, 1998).

Low average IQ is a common component of the SLI profile (Plante, 1998). The cognitive abilities of children with SLI may be poorer than their normally developing peers of the same age but have higher cognitive ability than normally developing peers of the same language ability (Hoffman & Gillam, 2004). The objective of the performance IQ cutoff of 85 (16th percentile) by Stark and Tallal (1981) was to ensure that IQ was above 70 (2nd percentile) in order to establish that substantial discrepancy existed between language and IQ measures (Bishop, 1997). This arbitrary nature of the cutoff of 85 (16th percentile) can, however, result in exclusion of children with definite linguistic characteristics of SLI but somewhat poorer IQ measure but without any gross intellectual impairment (Bishop, 1997; Weismer et al. 2000). Weismer et al., (2000) studied four groups of children: a group with normal language and nonverbal IQ of 85 or above, a language-impaired group with nonverbal IQ of 85 or above, a language-impaired group with nonverbal IQ between 70 and 84 and, finally, a group with normal language score but nonverbal IQ between 70 and 84. Both the language-impaired groups, one with lower nonverbal intelligence than the other, were found to perform poorly on phonological working memory tests compared not only to the group with normal language with IQ scores above 85 but also to the group with normal language and IQ between 70 and 84. Many would, therefore, like to see the stringent nonverbal performance criteria for cognitive ability in relation to the traditional definition of SLI to be reconsidered (Plante, 1998; Tager-Flusberg & Cooper, 1999).

If the impaired auditory temporal processing is causally related to SLI one would expect measures of impaired auditory temporal processing to relate to scores of receptive and expressive language and other important markers of SLI. Recent advances in thinking have seen the emergence and verification of psycholinguistic markers such as phonological memory as culturally unbiased diagnostic indicators of SLI (Conti-Ramsden & Hesketh, 2003; Weismer et al., 2000). Questions remain to be answered whether performance in temporal auditory processing tasks could be used as a marker for SLI and whether performance in temporal auditory processing tasks could predict various linguistic and nonverbal measures that define SLI and vice versa. Leonard (1998, p. 141) commented that the evidence for auditory processing tasks providing "a window into language skills of these children [SLI] . . . is far from perfect."

This article addresses auditory temporal processing ability in SLI, avoiding possible effects of frequency discrimination and task-related complexity on the auditory performance, in a frequency specific way. The AFT-R test is used and the auditory fusion thresholds of low-, middle- and high-frequency tones are compared between a strictly defined group of SLI children and an age- and gender-matched control group.

It is hypothesized that:

1. Children with SLI will require a longer time gap between two tones for them to be perceived separately, resulting in elevated AFT-R test thresholds,

compared to a control group, irrespective of the sound frequencies used, and that the threshold scores can predict the group membership.

2. The receptive and expressive language, nonverbal intelligence, and phonological working memory skills of the SLI group can predict the elevated AFT-R thresholds in this group, and vice versa.

METHODS

Participants

Nineteen children with SLI participated in this study. Children were recruited from speech and language caseloads and language units in the north west of England. Six girls and 13 boys between 88 and 142 months of age (mean 114.9, standard deviation 14.1) in the SLI group were compared with 19 controls, 6 girls and 13 boys, between 87 and 136 months of age (mean 115, standard deviation 16.5). All children in the control group had normally developing speech and language and had no history of problems in this domain. Each SLI participant was matched, as far as practicable in terms of age and gender, with a participant in the control group. The control group was recruited from mainstream schools in Manchester. The participants were recruited and tested after the parents and children had given written consent. The study was carried out after obtaining necessary approvals from the Local Research Ethics Committee in South Manchester and the University of Manchester. All the children had English as their first language and were free of any physical disability.

Audiological and Otological Inclusion Criteria Applicable for Both Groups

Otoscopy and relevant procedures such as removal of wax, tympanometry, and audiometry were carried out with all subjects to ensure that the ear canal was free of wax, middle ear was healthy, and hearing thresholds at 0.5, 1, 2, 3, and 4 kHz frequencies were 20 dB HL or better.

Language Measures for Inclusion in the SLI Group

1. *Receptive language score at least 2 years below chronological age.* This score was measured using the Test for Reception of Grammar (TROG) Second Edition (Bishop, 1989). TROG is a multiple-choice test of comprehension of grammatically complex sentences and uses clearly drawn and brightly colored pictures as test materials. In addition to age-equivalent scores, standardized scores with a mean of 100 and a standard deviation of 15 are available.

2. *Expressive language ability at least 1 year below the chronological age.* This ability was measured by the expressive language quotient of the Clinical Evaluation of Language Fundamentals-Third Edition (CELF-3; Semel et al., 1995) derived from the Word Structure, Formulated Sentences, and Recalling Sentences subtests that evaluate production of English morphological rules in a sentence-completion task, the ability to assemble sentences of varying syntactic and semantic complexity in response to an orally presented target word in the context of a stimulus picture, and ability of recalling/imitating sentences of varying length and syntactic complexities, respectively. For children in the age range studied here, the Recalling Sentences and Formulating Sentences subtests provide standardized scores, which have a mean of 10 and a standard deviation of 3.

3. *Nonverbal ability above the 10th percentile that represents a nonverbal IQ above 80 (9th percentile).* This ability was measured by Raven's Colored Progressive Matrices (CPM; Raven, Raven, & Court, 1995). This test is a multiple-choice task to match patterns that evaluates intellectual processes. Issues surrounding the precise level of nonverbal IQ have already been discussed at the beginning of this article.

Language Measures for Inclusion in the Control Group

Children in the control group had age-appropriate-scores on TROG and nonverbal performance above the 10th percentile measured by Raven's CPM. They also had receptive vocabulary scores above the 25th percentile, measured by the British Picture Vocabulary Scale, Second Edition (BPVS-II; Dunn et al., 1997). The relatively high sensitivity compared to a low specificity of CELF makes it a useful tool for identifying a child as language impaired; however, it is less useful at correctly identifying a nonimpaired child as "nonimpaired." Therefore, use of the CELF was restricted to identifying SLI participants, whereas the BPVS (with higher specificity) was used to screen for language impairment in controls.

Additional Language Measures

Children with SLI participated in additional assessments for a better understanding of their abilities and also to explore the possibilities of any relationship to temporal processing.

1. Children's Test of Nonword Repetition (CNRep; (Gathercole & Baddeley, 1996) was used to assess phonological working memory. In this test children are asked to repeat spoken, phonologically complex nonwords that follow English phonetic constraints.
2. British Picture Vocabulary Scales (BPVS-II; Dunn et al., 1997). Both control and SLI children participated in this test of receptive vocabulary.
3. Expressive phonological ability was measured as a percentage of correct productions, out of a possible 38 phonemes, in initial and final position using a nonstandardized picture-naming task.
4. Renfrew Action Picture Test (RAPT; Renfrew, 1997) was carried out to evaluate language in terms of expression of information (verbal formulation) and grammatical accuracy.

THE AUDITORY FUSION TEST-REVISED

The Auditory Fusion Test-Revised (AFT-R) by McCroskey and Keith (1996), commercially marketed by AUD*i*TEC™ of Saint Louis, was used to determine the gap detection abilities of control and SLI subjects. Stimulus test tones were played on a high-quality CD player and presented through speakers. Testing started with a practice and screening subtest in which a brief 500 Hz calibration tone was followed by 500 Hz tone pairs, with gaps between the tone pairs also called interpulse intervals (IPI). The intervals progressively increased from 0 to 300 milliseconds (ms). Subjects were asked to indicate if they heard "one" or "two" tones, which were presented at 50 dB SL. The practice sessions were repeated several times until the subjects responded consistently to the practice tones.

Once a consistent response was obtained, the main body of the test was administered using three sound frequencies (0.25, 1, and 4 kHz). Each frequency was tested separately in random order. Tests for each frequency had two components. In the first component—the ascending set—the interval between tone pairs (IPI) increased progressively at each successive presentation. IPIs were: 0, 2, 5, 10, 15, 20, 25, 30, and 40 ms. The ascending set was followed by the second component—the descending set—in which the IPI between the tone pairs decreased progressively in the order 40, 30, 25, 20, 15, 10, 5, 2, and 0 ms. Participants were again required to indicate if they heard one or two tones for each pair of tones presented. The IPI of the last one response before consecutive two responses was noted as the auditory fusion point (AFP) for the ascending set and the IPI of the first of two consecutive one responses for the descending set was taken as the AFP for the descending set. The average of ascending and descending AFP values represented the auditory fusion threshold (AFT) for the frequency tested.

RESULTS

The data were analyzed using SPSS 11.5.

Language Data Comparing the SLI and Control Groups

The comparative performances of the SLI and control children on tests of language and nonverbal ability that were carried out in both groups are provided in Table 2. The age equivalent and standardized scores for TROG and BPVS clearly show the language delay in the SLI group. The nonverbal intelligence of the SLI group was also lower compared to the control group.

Addition Language Assessments in the SLI Group

Table 3 provides the performances of additional assessments that were carried out only in the SLI group in order to get a better understanding of the profile of the SLI group and to explore any relationship to the temporal processing ability.

AFT-R Data and Analysis

The mean and standard deviations of the scores on AFT-R are shown in Table 4. Four SLI subjects, one female and three males, were unable to perform the test with consistency at all the frequencies tested, whereas one male and one female subject in the control group were inconsistent. These six children were excluded from further analysis. Figure 1 shows a box plot for the AFT scores at the three frequencies in the two groups. SPSS version 11.5 was used to explore and analyze the data. Kolmogorov-Smirnov tests demonstrated that data distributions were not significantly different from normal ($p > 0.05$).

TABLE 2. Comparative measures of some language tests and nonverbal intelligence.

	SLI (N = 19)			Control (N = 19)		
	Mean	**SD**	**Range**	**Mean**	**SD**	**Range**
Actual age in years	9.5	1.1	7.3–11.8	9.5	1.38	7.2–11.3
TROG raw score	12	2.2	8–16	17.3	1.9	14–20
TROG standard score*	76	5.9	66–86	105.5	12.7	87–132
TROG age equivalent (years)	6	1.2	4.25–9	9.8	1.4	7–11
BPVS raw score	71.8	13.8	55–103	99.6	19.9	67–136
BPVS standard score*	82	8.1	69–105	105.5	11.9	91–131
BPVS age equivalent (years)	7.1	1.4	5.4–10.8	10.5	2.8	6.5–16.3
CPM raw score	27.3	5.4	17–36	30.9	3.3	24–36
CPM percentile	53.7	31.6	10–95	78.2	20.3	37–95

*TROG and BPVS provide standardized scores, with a mean of 100 and standard deviation of 15.

TABLE 3. Measures of language that were carried out only in the SLI group.

	Mean	**SD**	**Range**
CELF Sum of 3 subset raw scores	48.6	20.6	17–86
CELF Expressive age equivalent in years	5.8	0.9	4–7.5
CELF Formulated Sentences raw score	12.6	8.8	0–32
CELF Formulated Sentences standard score*	3.6	1.5	3–9
CELF Recalling Sentences raw score	18	7.8	8–33
CELF Recalling Sentences standard score*	3.4	1	3–7
Phonological screening	93.3	9.6	55–100
RAPT Information raw score	29	3.8	23–37
RAPT Information age equivalent in years	4.5–4.9		
RAPT grammar raw score	23.4	4.3	12–30
RAPT grammar age equivalent in years	5–5.4		
CNRep raw score	21.6	8.4	6–32

*Formulating Sentences and Recalling Sentences subtests of CELF[3] provide standardized scores, which have a mean of 10 and a standard deviation of 3.

Effect of Frequency on Gap Detection Ability

To find out which test frequency is most likely to identify larger proportions of children with SLI, binary logistic regression was carried out using the study group (Control vs. SLI) as outcome and the auditory fusion thresholds at the three different frequencies as predictors. If all subjects in the data were considered to be in the control group, this would have been correct 17 times out of 32 (i.e., 53.1%) with 100% and 0% accuracy of prediction for the control and SLI groups, respectively. A stepwise

TABLE 4. Auditory fusion thresholds for the three experimental frequencies.

	AFT 0.25 kHz	AFT 1 kHz	AFT 4 kHz
SLI Group			
Mean	10.83	9.66	10.36
Standard deviation	4.01	6.16	4.87
Control Group			
Mean	10.33	7.36	6.94
Standard deviation	6.79	5.10	4.84

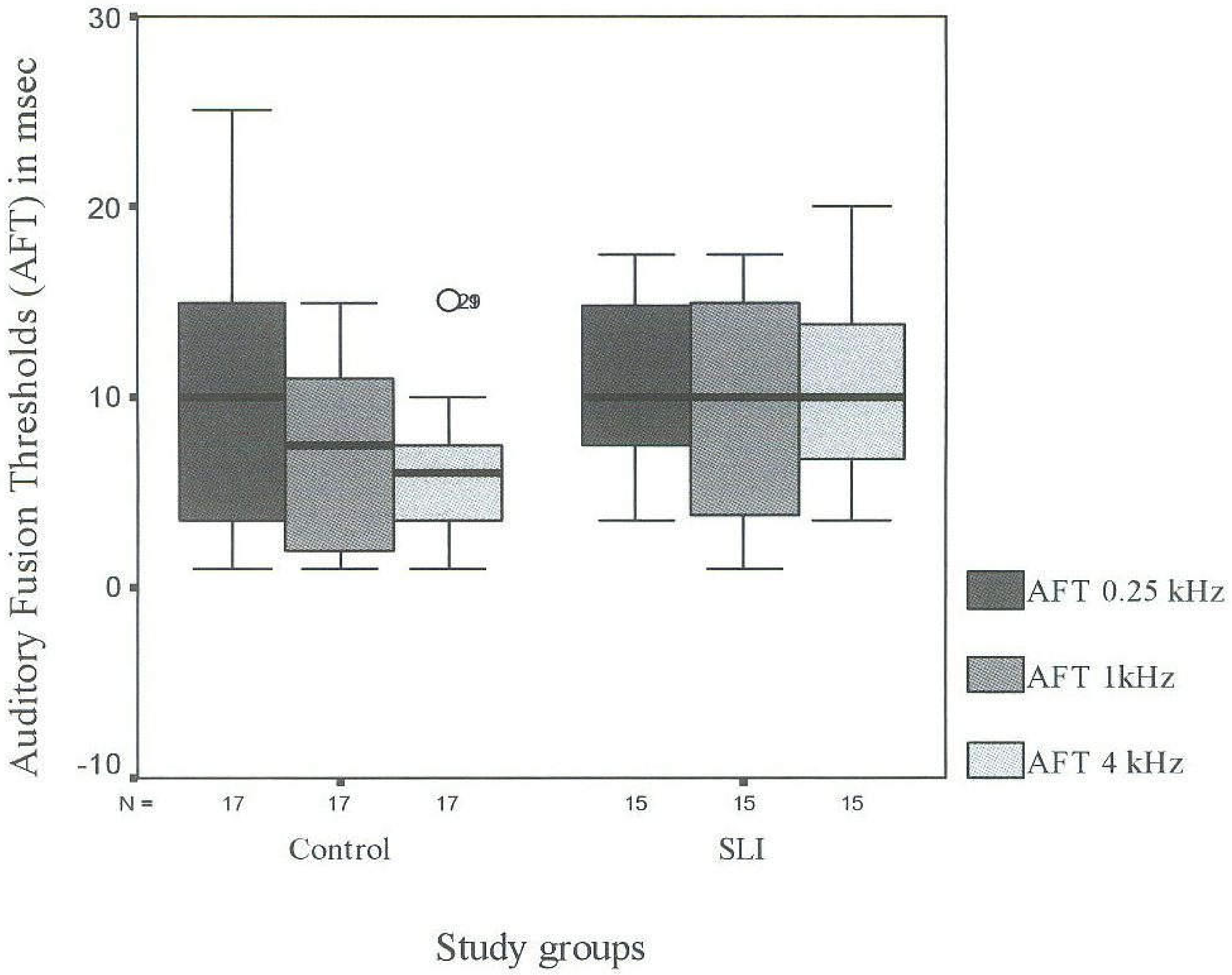

Figure 1. Box plot showing AFT scores at three frequencies in the two study groups.

regression method was used, as this mode is regarded to be more appropriate for exploratory work (Field, 2000), to see if any other models could improve the prediction. A stepwise backward logistic regression method was preferred because the model starts with all the predictors included and, therefore, reduces the chance of type II error (Field, 2000). The AFTs at 1 kHz and 0.25 kHz did not contribute significantly to the model and were removed at step 2 and step 3, respectively. The AFT at 4 kHz significantly predicted ($p < 0.05$) the group membership of the subjects in the study and was not removed from the model. The model using AFT at 4 kHz tone predicted 82% of the subjects in the control group and 60% of those in the SLI group. The overall percentage of correct prediction improved from 53 to 72%. Use of the Hosmer and Lemeshow test confirmed that the model with 4 kHz as the predictor tone was a good fit to the data. The Wald statistics value of 4.744 suggested that the , coefficient for the 4 kHz predictor of 0.204 was significantly different from zero ($p < 0.05$). The exp β an indicator of the change in odds resulting from a unit change of the predictor, was 1.226, with the value varying in the population between 1.021 and 1.472 in 95% of occasions. Values greater than 1 indicate higher AFTs at 4 kHz in the SLI group. The analysis rejected 0.25 and 1 kHz as predictors because they did not improve the model to any significant extent.

Figure 1 illustrates the spread of the AFT scores at the three frequencies in the two study groups. There is some overlapping of scores between the two groups, with the least overlap at 4 kHz, and at this frequency the overlap is noted for scores below 10 ms. Therefore, we subdivided the results of the study groups into two subgroups: one with AFT scores less than 10 ms (better gap detection ability), which will be termed the Low AFT group (LAG), and a second subgroup with AFT scores of 10 ms and higher (poorer gap detection ability), which will be termed the High AFT group (HAG). Binary logistic regression was carried out in a manner described previously to see if HAG and LAG categories could predict membership of subjects in the SLI and control groups. The regression model suggested that HAG and LAG subgroups based only on the AFT at 4 kHz were statistically significant and predicted 82% of the subjects in the control group and 60% of those in the SLI group, with an overall predictive value of 72%. The HAG and LAG categories based on AFTs at 1 kHz and 0.25 kHz did not significantly predict the group membership of the subjects in the study and were removed from the model in step 2 and step 3, respectively. A number of statistics including Chi-square confirmed that the 4 kHz predictor was significant ($p < 0.05$). A Wald statistics value of 5.548 suggested that the β coefficient, for the HAG and LAG categorical predictors, of –1.946 was significantly different from zero ($p < 0.05$). The exp β, was 0.143, with the value varying in the population between 0.028 and 0.721 in 95% of occasions. Values less than 1 confirm that a higher proportion of SLI subjects will be in the HAG category based on AFT at 4 kHz.

Effect of Age and Gender on AFT at 4 kHz

Univariate analysis was carried out with AFT 4 kHz as the dependant variable, the study group and gender as fixed factors, and age as a covariate. The analysis here includes partial eta squared (η_p^2), a measure of the effect, and the statistical power in addition to the F ratio and significance. The analysis suggested that AFT at 4 kHz was significantly different between SLI and the control groups (F (1, 28) = 11.366, $p < 0.005$, $\eta_p^2 = 0.289$, observed power 90%). The between subjects effect of age (F (1, 28) = 0.003, $p > 0.05$, $\eta_p^2 = 0.000$, observed power = 5%) and gender (F (1, 28) =1.254, $p > 0.05$, $\eta_p^2 = 0.043$, observed power = 19%) were not significant. The data meet the requirement of the Levene's test of homogeneity of variance ($p > 0.05$) for the univariate analysis to be valid. Figure 2 shows a plot of the output from SPSS that demonstrates that girls had higher AFT 4 kHz values than boys in the SLI group. This interaction between groups and gender was significant ($p < 0.05$), but the observed power was low (F (1,28) = 4.647, $p = 0.04$, $\eta_p^2 = 0.142$, observed power = 54.8%)

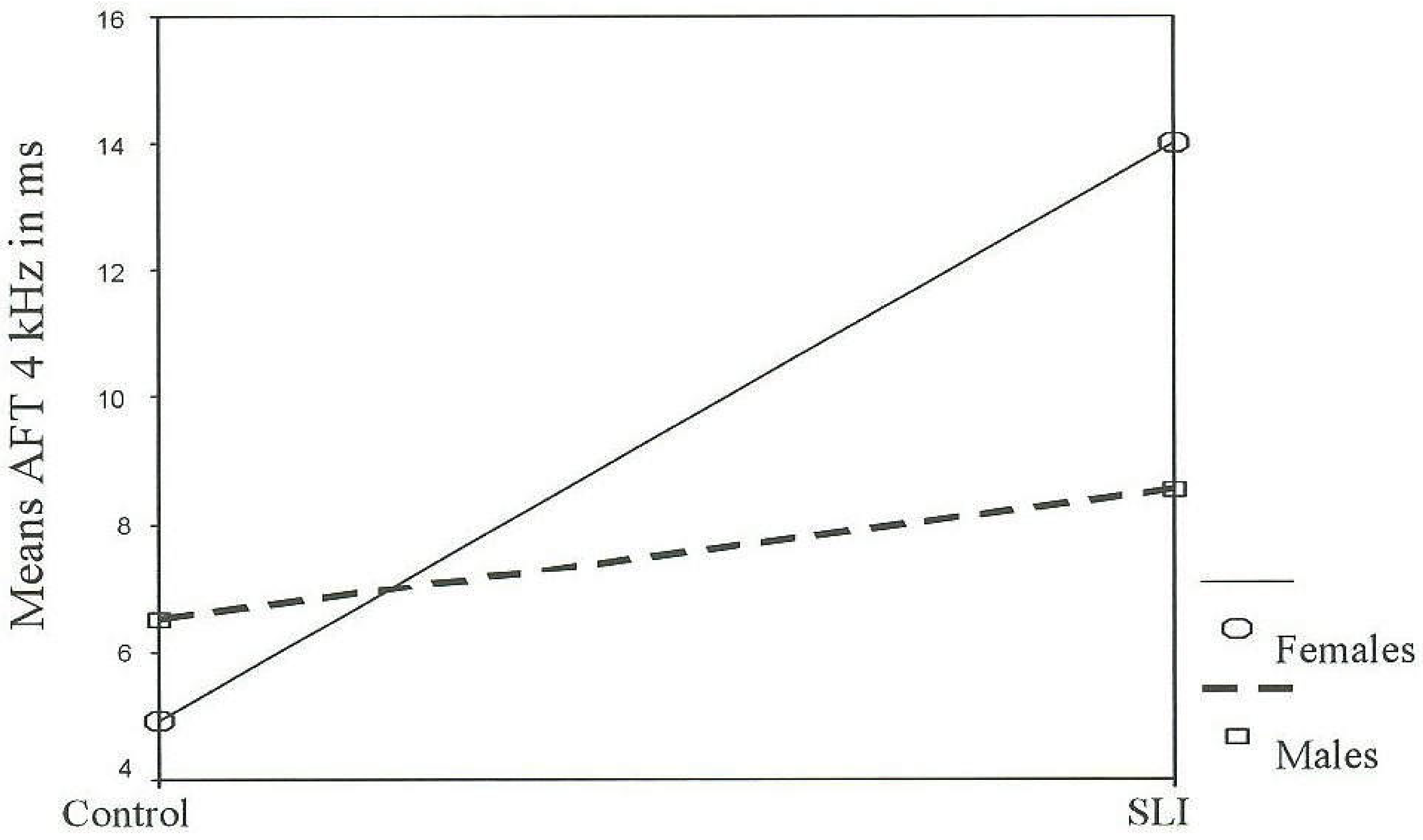

Figure 2. Graphical representation of the interaction between gender and groups in respect of the AFT 4 kHz scores.

Pearson's correlation coefficients for the relationship between age and AFT 4 kHz scores were sought, and this was not significant either in the SLI group (r = 0.315, $p > 0.05$) or the control group (r = –0.174, $p > 0.05$). The scatterplots showing the relationship between AFT 4 kHz and age for the SLI and control groups are shown in Figures 3 and 4, respectively.

Relationship Between AFT-4 kHz Scores and Language/Nonverbal Performance Measures

Multiple regression analyses were carried out to see if the raw scores of tests assessing receptive and expressive language abilities and phonological memory could be predicted using age, nonverbal intelligence, gender, and AFT 4 kHz as predictors. In view of the exploratory nature of our effort, a stepwise backward model was chosen (Field, 2000). In this method all the predictors are entered in a model and the contribution of each predictor is calculated. If a predictor fails to contribute significantly, it is removed and the rest of the predictors re-evaluated. Nonsignificant predictors are removed one at a time in a stepwise fashion, the most nonsignificant predictor being removed first, until all the nonsignificant predictors are removed. The results outlined in Table 5 show that AFT 4 kHz could not predict any measures of the language or phonological memory assessment in the SLI children.

A stepwise backward multiple regression analysis was also done with TROG, BPVS, CELF Exp, RAPT grammar and information, Raven's CPM and CNRep scores as predictors, and AFT 4 kHz scores as the outcome. The analysis found none of these predictors were significant ($p > 0.05$) in predicting the AFT 4kHz scores. The nonsignificant ($p > 0.05$) relationship between AFT 4kHz scores and that of the nonverbal intelligence in the SLI group is represented graphically in Figure 5.

DISCUSSION

Temporal Resolution and Frequency

The results of this study show that the SLI group had significantly elevated auditory fusion thresholds or poorer temporal resolution compared to the control group only at 4 kHz. Our data therefore supports the first hypothesis for 4 kHz tones but not for 0.25 and 1 kHz tones. These findings are partly congruent with those of McCroskey and Kidder (1980), who found a significantly elevated AFT in children with reading and learning disabilities

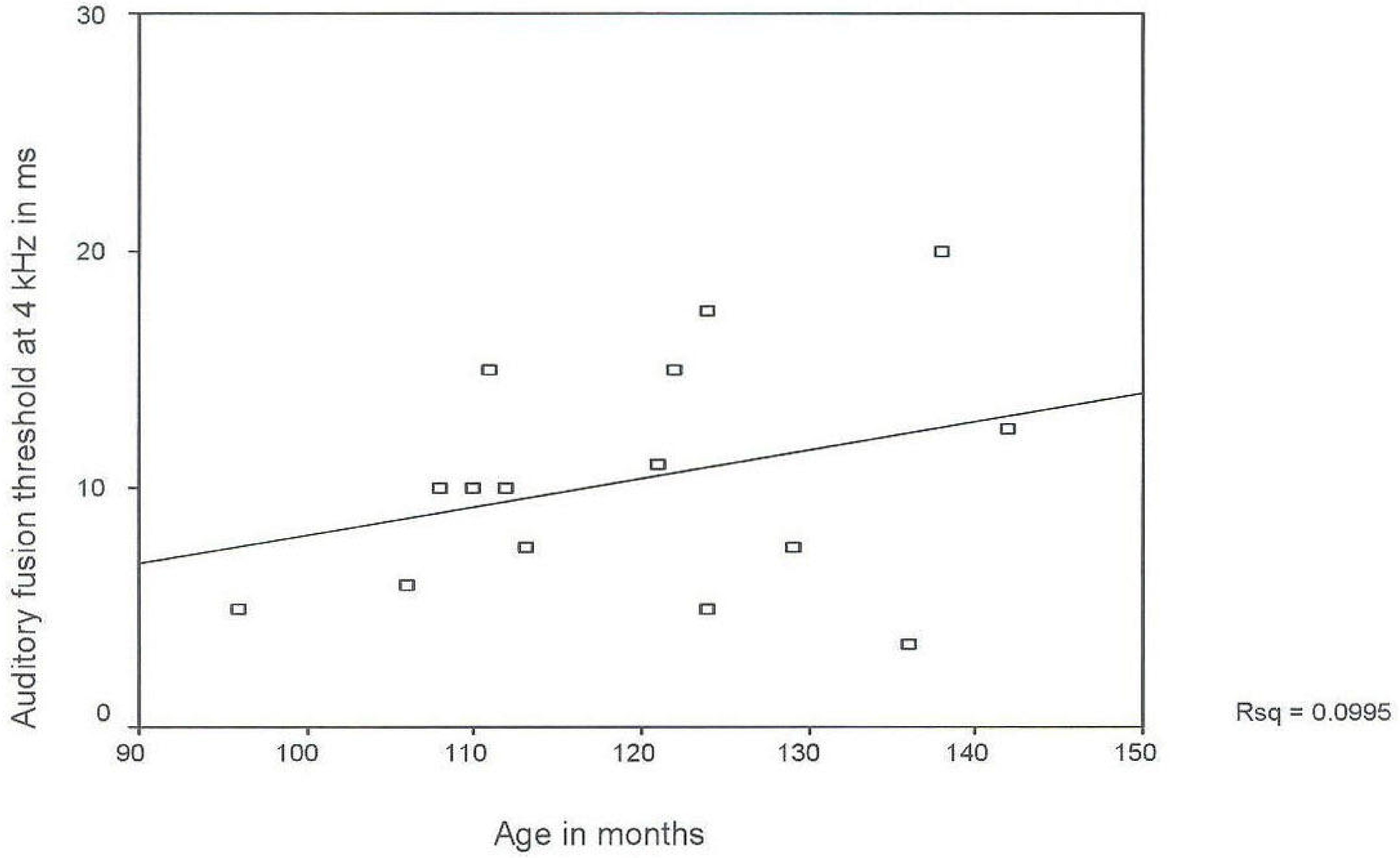

Figure 3. Scatterplot with regression line to show the correlation between the AFT 4 kHz scores and the age in the SLI group.

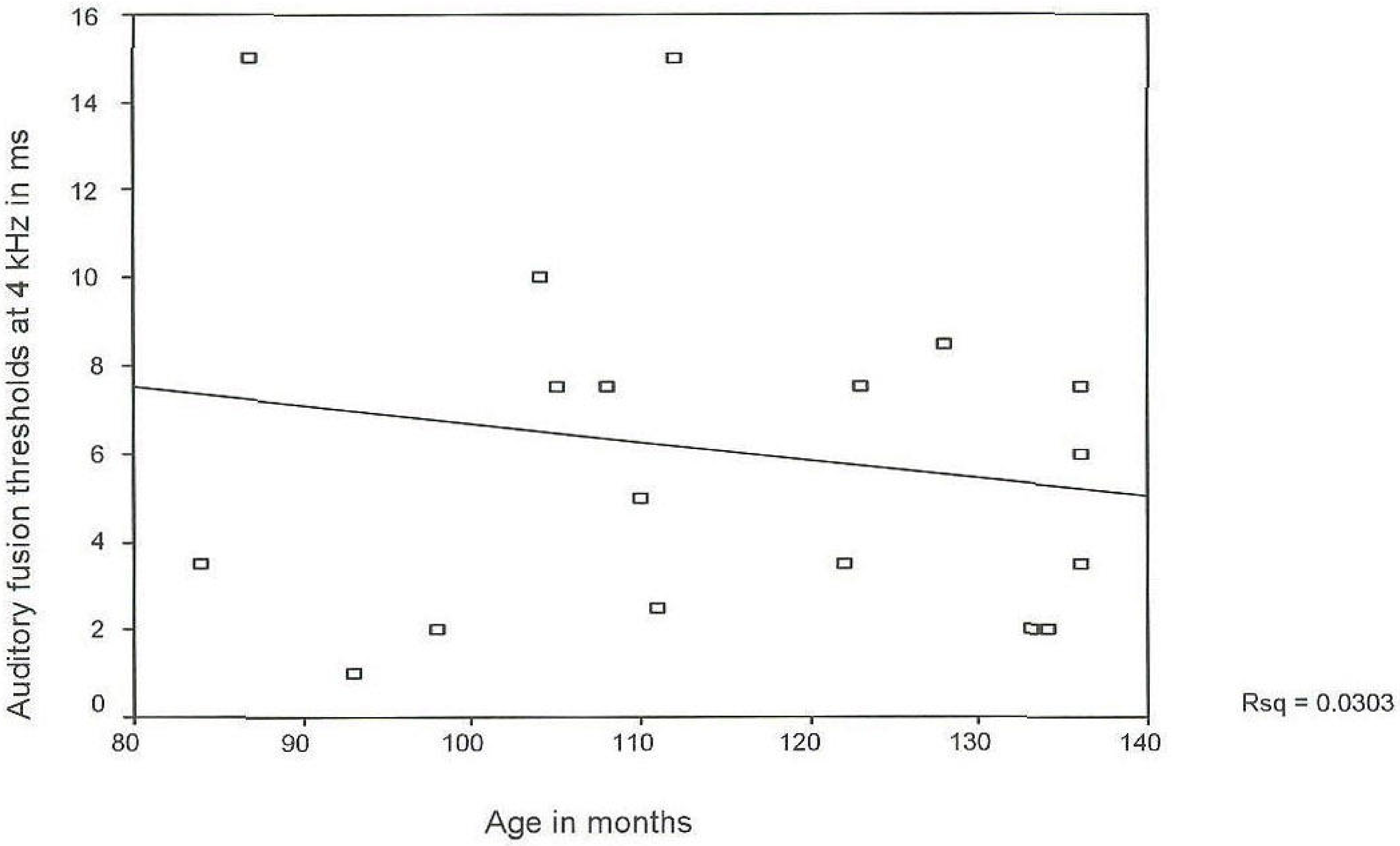

Figure 4. Scatterplot with regression line to show the correlation between the AFT 4 kHz scores and the age in the control group.

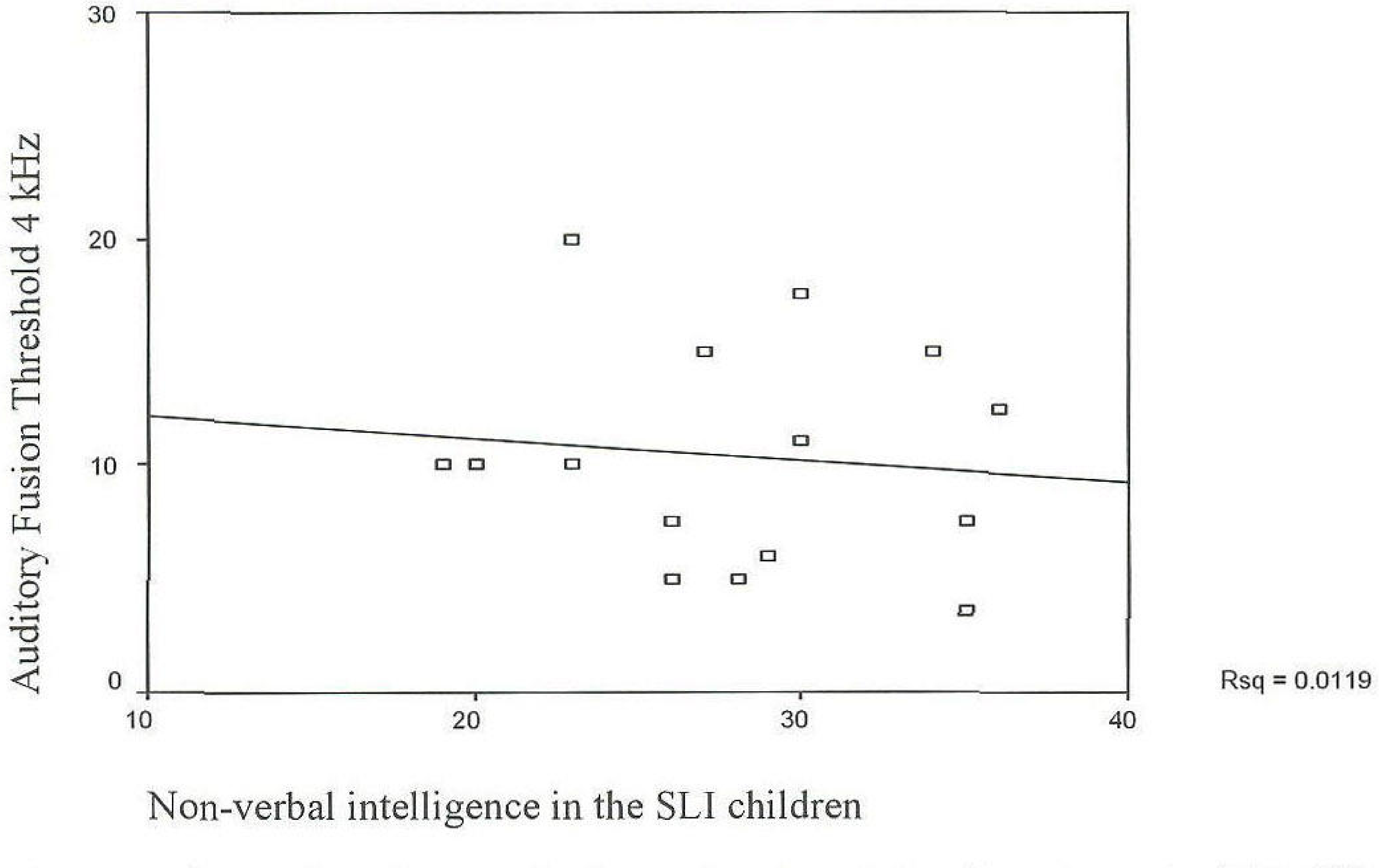

Figure 5. Scatterplot with regression line to show the relationship between the AFT 4 kHz scores and nonverbal intelligence in the SLI children.

at 0.25, 0.5, 1, 2, and 4 kHz, and the performances at 0.25 and 4 kHz were more severely affected than the other frequencies. However, it is clear that these two studies were investigating different populations. The difference in the AFT 4 kHz scores between the SLI and control groups in our study was not influenced by the age or gender distribution between the groups and, hence, the poor performance by the SLI children is likely to be associated with the condition. The impaired temporal resolution at 4 kHz in SLI children compared to the lower frequency tones can be explained by constraints in cortical neural processing in SLI, and this view finds support from Lockwood et al.'s (1999) sugges-

TABLE 5. Backward stepwise multiple regression analysis in the SLI group, predicting receptive and expressive language and phonological memory scores, with age, nonverbal intelligence, gender, and AFT 4 kHz as predictors.

Language Tests	Partial Correlation[1]	Unstanderdized Coefficient, β[2]	*t* Test[2]	P[4]
TROG	.036	.010 (–.194 – .215)	.112	.913
CELF Expressive	.036	.124 (–2.546 – 2.298)	.114	.911
Formulated sentences subset	–.177	.220 (–1.087 – .646)	–.567	.583
Recalling sentences subset	–.108	–.181 (–1.360 – .997)	–.343	.739
BPVS	.055	.128 (–1.495 – 1.751)	.175	.864
CNRep	–.315	–.564 (–1.763 – .635)	–1.048	.319
RAPT grammar	–.021	–.016 (–.565 – .532)	–.067	.948
RAPT information	.20	.116 (–.286 – .518)	.645	.534

[1] Partial correlation (N = 15) between language tests and AFT 4 kHz, after controlling for age, nonverbal intelligence, and gender.

[2] β represents the change in language scores for a unit change in AFT 4 kHz, with 95% confidence interval in parentheses.

[3] *t*-test assesses if the β value is different from zero, that is, statistically significant.

[4] Significance of AFT 4 kHz as a predictor of language test scores.

tion that higher frequency sounds (4 kHz tones) involve more central neural processing compared to lower frequency sounds (0.5 kHz tones).

Temporal Resolution and Gender

One of the incidental findings of our data was an interaction effect of gender and groups on the temporal resolution ability. The female participants in the SLI group were found to have poorer temporal resolution than the males. The observed power of the statistical analysis was only 54.8%, and the significance at α level of 0.05 was lost if the power was increased to 80%.

In health there is a gender difference in auditory processing, with a right ear advantage in males for rapid auditory temporal processing (Brown et al., 1999; Efron et al., 1983) and gap detection tasks (Brown & Nicholls, 1997), probably due to a larger left planum temporale. A recent functional MRI study (Kansaku et al., 2000), however, shows no gender differences in functional activation of the temporoparietal cortex that is involved in auditory processing that requires temporal resolution such as phonological processing. One way interhemispheric transfer requires about 25 ms, so there is not enough time for auditory temporal processing to involve two hemispheres (Ringo et al., 1994). The left brain is involved in both genders for such processing. It is suggested that females have more prominent isthmus of the corpus callosum, allowing more efficient communication between the two hemispheres resulting in bilateral processing of linguistic and other less time-critical functions.

Females not only need more severe neuropathology of the brain in order to exhibit behavioral problems but also recover from neural insults more readily than males. Aphasia, resulting from damage to the left hemisphere, occurs in males three times more commonly than in females. SLI is more common in males (Leonard, 1998, p. 3), but it is not clear from the literature if male children with SLI have a higher incidence of impaired temporal processing ability. Many studies have looked at auditory processing in SLI children (Bishop, Bishop et al., 1999; McArthur & Bishop, 2004; McArthur & Hogben, 2001; Neville et al., 1993; Norrelgen et al., 2002), but it is difficult to conclude about auditory temporal processing abilities in terms of gender differences. Some studies only included males (Robin et al., 1989) and some studies had only few females (Wright et al., 1997), making it difficult to conclude regarding gender differences.

A recently proposed model, which links dyslexia and neurodevelopmental disorders like SLI to microgyri and cerebral ectopia, suggests an increased prevalence of sensorimotor syndromes that included phonological and auditory processing deficits in males (Herman et al., 1997; Peiffer et al., 2002; Ramus, 2004). This has been attributed to the sex differences in cortical anomalies or differences in sex hormone mediated thalamic disruption. Such conclusions are based on studies in rats. However, a closer look at the stimulus paradigm of these experiments raises the question of whether the poor response in the male rats with microgyri was due to impaired temporal resolution or frequency discrimination. Peiffer et al. (2002) showed that the male rats with induced microgyri performed poorly in discriminating two tones, 1100 Hz and 2300 Hz, at short ISI but not at a longer ISI. Fitch et al. (1994) tested the effect of duration of tone pairs on discrimination and found that male rats with induced microgyri performed poorly at shorter stimulus duration compared to the male rats without microgyri.

In view of the literature, and the fact that 3 of the 4 children out of the 19 SLI children who failed to reliably perform the AFT-R were males, we were initially hesitant in accepting our finding of females performing poorly in an auditory temporal resolution task. However, a parallel study using the same subjects, to be reported separately, showed that females in the SLI subgroup who performed poorly on a temporal resolution task performed better in a frequency discrimination task compared to the subgroup with better temporal resolution. In other words, SLI boys showed poorer frequency discrimination ability. The effect of gender on auditory processing in SLI children in our study therefore suggests that the auditory processing abilities in SLI need to be assessed separately for both temporal resolution and frequency discrimination. The finding of an inverse relationship between temporal resolution and frequency discrimination abilities in SLI is consistent with the hypothesis (Zatorre, 2001) that links such dissociation to hemispheric specialization. The left auditory cortex demonstrates better temporal resolution than the right side, which is more sharply tuned for frequency discrimination (Tervaniemi & Hugdahl, 2003; Zatorre, 2001). Structural and functional asymmetry between males and females (Brown et al., 1999) may explain the gender differences in temporal resolution and frequency discrimination.

SLI Subgroups Based on Temporal Resolution Ability at 4 kHz

The analysis of our data strongly supports two subgroups of SLI based on AFT 4 kHz scores. For the age group included in our study, one subgroup (LAG) had scores below 10 ms, and the other subgroup (HAG) had scores of 10 ms or more. This 10 millisecond threshold value for differentiating between better temporal resolution in one group and relatively poorer temporal resolution in the other was confirmed statistically by binary logistic regressions, as the HAG/LAG categorical subgrouping had the same overall predictive ability of 72% to differentiate between SLI and control groups as the individual AFT 4 kHz threshold scores.

There are variations in the exact gap detection thresholds quoted in the literature for healthy individuals. Joliot et al. (1994) compared the gap detection thresholds using psychophysical methods with that obtained by an objective measure called Magnetic Middle latency auditory evoked fields (MAEF) in 9 adult males using paired click stimuli. Two separate 40 Hz responses were generated for gaps of 12 ms and above, whereas for gaps less than 12 ms only one 40 Hz response was obtained, and this also matched the perception of two sounds for gaps of 12 ms or longer and one sound for gaps less than 12 ms. Such results contradicts the findings of Rupp et al. (2002) who also used MAEF as an objective tool but got responses at 3 ms that matched well to psychophysical gap detection thresholds of 2 ms. Bertoli et al. (2001) on the other hand used Mismatch Negativity (MMN) as the objective measure of gap detection in 10 adult subjects and found that psychophysical gap detection threshold was around 6 ms but MMN responses were demonstrable for gaps of 9 ms and over. Values of AFT 4 kHz below 10 ms, as evidence of good temporal resolution, is therefore consistent with the literature. SLI is therefore not only heterogeneous in terms of the linguistic and cognitive abilities (Bishop, 1997) and association with other neurodevelopmental disorders (Bishop, 1997; Estil et al., 2003; Hill, 2001; McArthur et al., 2000; McArthur & Hogben, 2001; Neville et al., 1993), but also in terms of their auditory temporal processing abilities.

Temporal Resolution and Language and Nonverbal Performance in SLI

Our second hypothesis was rejected as the AFT 4 kHz scores, despite being significantly poorer in the SLI group compared to the control group, did not have any predictive effect on the raw scores of different tests known to be markers of SLI and vice versa. Tallal et al. (1985) demonstrated the ability of ART using speech and nonspeech sounds of various duration (time gaps between the sound pairs were constant) in predicting the receptive language abilities measured by Token Test, Test of Auditory Comprehension of Language, receptive portion of Northwest Syntax Screening Test, and Auditory Reception and Auditory Association Subtests from the Illinois Test of Psycholinguistic Abilities. Bishop, Bishop et al. (1999) on the other hand demonstrated that ART was able to predict the receptive language ability of SLI children using the TROG test but not using Wechsler comprehension from the third revision of the Wechsler Intelligence Scale for Children (WISC-III). ART was also not able to predict the expressive language abilities using Repeating Sentence and Word Finding subsets of CELF, and test of phonological memory using CN-Rep test. Questions arise why impaired auditory temporal processing predicts only certain receptive language tests and none of the tests of expressive language when both receptive and expressive languages are affected by SLI. In contrast to the Tallal et al. (1985) study, Bishop, Bishop et al. (1999) used two different time intervals between the stimulus pairs and found that the SLI children performed poorly in the ART task irrespective of the rate of stimulus presentation and, hence, both the Tallal et al. (1985) and Bishop, Bishop et al. (1999) studies probably demonstrated slower information processing by SLI rather than slower temporal auditory processing. Leonard (1998, p. 141) suggests that "many aspects of language do not depend on the ability to process brief acoustic details, and when such brief details are encountered, additional cues are often available" and therefore the redundancies in language could explain the lack of relationship between language measures and temporal resolution abilities for tones. However it is a possibility that the relationship between temporal resolution and language development exists in the early years (Trehub & Henderson, 1996), and as the children mature and support is provided for their language impairments the relationship no longer exists. Tallal et al. (1996) demonstrated a remarkable improvement of comprehensive language scores following 4 weeks of training with acoustically modified signals. However, it is unlikely that the SLI children learned the equivalent of 2 years of language in a month, and Tallal et al. (1996) suggest that SLI children have better language competence than they can demonstrate.

The failure to find relationships between any marker of language impairment and performance on the AFT suggests that temporal resolution of tones may not be causally related to linguistic ability, a possibility that was also echoed by Bishop, Carlyon et al. (1999). The possibility of the lack of direct correlations between auditory temporal processing and measures of language and nonverbal performance may be explained by the involvement of different areas of the brain in processing speech (Gernsbacher & Kaschak, 2003; Horwitz & Braun, 2004) and nonspeech sounds (Nenadic et al., 2003). Different aspects of speech processing such as phonological, lexical, syntactic, and semantic processing also involve different areas of the brain (Gernsbacher & Kaschak, 2003). Variations in the extent of the brain areas involved and variations in the degree of functional impairment of the neurons, involved by the yet unexplained underlying pathophysiological mechanism causing SLI, in individual subjects could therefore be a possible explanation of the heterogeneity of SLI in terms of both their language abilities and temporal processing of tones.

Other Possibilities for SLI Subgroups Based on Temporal Resolution Ability

Normal hemispheric asymmetry is important for the timing mechanism associated with temporal resolution (Harrington et al., 1998; Tervaniemi & Hugdahl, 2003; Zattore, 2001). The left auditory cortex is more sensitive to temporal changes (Belin et al., 1998; Liégeois-Chauvel et al., 1999). Therefore, the right hemispheric dominance seen in SLI subjects (De Fossé, 2004) could also explain their poorer temporal resolution. If all SLI children have right hemispheric dominance, the poorer temporal resolution ability is expected to be present in all SLI children, and this is clearly not the case, leaving scope for exploring other possibilities.

It could be speculated that the SLI subgroup with poorer temporal resolution abilities, in addition to their cerebral cortical involvement to account for their SLI, have additional involvement of other central nervous system (CNS) structures. SLI is associated with a number of other neurodevelopmental disorders and difficulties in motor function (Estil et al., 2003; Hill, 2001; McArthur & Hogben, 2001; McArthur et al., 2000; Ramus, 2004; Redmond, 2004). Some of these conditions are also associated with impaired temporal auditory processing. The auditory impairment in these various conditions may result from involvement of structures like the auditory relay station in the medial geniculate body (Ramus, 2004), basal ganglion (Gräber et al., 2002; Nenadic et al., 2003) and cerebellum (Ivry & Spencer, 2004; Keele et al., 1985). In their literature review, Ivry and Spencer (2004) have shown consistent evidence of involvement of the cerebellum in temporal information processing, not only for motor tasks but also for tasks involving perceptual discrimination and phonemic perception. In a fMRI study using time estimation and frequency discrimination tasks, Nenadic et al. (2003) found that right medial and both left and right dorsolateral prefrontal cortex, thalamus, basal ganglia (caudate nucleus and putamen), left anterior cingulated cortex, and superior temporal auditory areas were involved in auditory processing. When the time estimation and frequency discrimination tasks were compared, it was found that activities in the right putamen were restricted to the time estimation task. Ivry and Spencer (2004) have proposed models linking the basal ganglia with the prefrontal cortex and other cortical areas in maintaining "cognitive timing." Further studies are required in children with SLI to assess the functional interactions between the basal ganglion, cerebellum, and the cerebral cortical areas by combining neural networking modeling and functional neuroimaging, a method found to be informative by Horwitz and Braun (2004) in investigating language processing in the brain.

CONCLUSION

The first goal of this study was to assess if inclusion of 4 kHz tones in psychoacoustic tests for temporal resolution would be better than tones at lower frequencies to detect impairment in auditory temporal resolution. The results of our study support the proposition that the use of 4 kHz tones would be more efficient in categorizing children with SLI according to their temporal resolution ability.

The second aim was to see if the linguistic and nonverbal abilities in SLI children were related to their temporal resolution ability. Our results failed to show any relationship between temporal resolution ability and competence on language and nonverbal performance tasks. This study also shows the existence of two subgroups of SLI: one with relatively better and the other with relatively poorer temporal resolution ability irrespective of their linguistic and cognitive abilities. Additional findings suggested poorer temporal resolution in girls compared to boys with SLI. We propose that inclusion of the more sensitive frequency of 4 kHz in testing may have revealed a more consistent pattern of auditory temporal processing impairment in children with SLI and that the variability in the existing literature may be due to testing with less sensitive frequencies.

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