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Association between temporal resolution and Specific Language Impairment: The role of nonsensory processing

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A B S T R A C T

Introduction: Many authors have suggested that a perceptual auditory disorder involving temporal processing is the primary cause of Specific Language Impairment (SLI). The aim of this study was to compare the performance of children with and without SLI on a temporal processing task controlling for the confounding of verbal short-term memory and working memory.
Method: Thirty participants with SLI aged 6 years were selected, along with 30 age- and gender-matched participants with typical language development. The Adaptive Test of Temporal Resolution (ATTR) was used to evaluate temporal resolution ability (an aspect of temporal processing), and the digit span subtest of the Wechsler Intelligence Scale for Children was used to evaluate auditory short-term memory and working memory.
Results: The analysis of covariance showed that children with SLI performed significantly worse than children with typical language development on the temporal resolution task (ATTR), even when controlling for short-term memory and working memory. Statistically significant correlations between ATTR and digit span were found for the group of children with SLI but not for the children with typical language development.
Conclusion: Children with SLI showed significantly worse temporal resolution ability than their peers with typical language development. Such differences cannot be attributed solely to the immediate memory deficit associated with SLI.

1. Introduction

Children with Specific Language Impairment (SLI) show difficulty in both language comprehension and expression. SLI is by definition a significant language disorder that cannot be explained by auditory, cognitive, neurological, or oral motor problems [1].

Regarding the cause of this disorder, authors as early as 40 years ago suggested that an auditory perceptual deficit connected to temporal processing may be the primary dysfunction underlying SLI [2–5]. From an auditory perspective, temporal processing is defined as the perception of sound or the alteration of sound within a restricted or defined time domain [6]. Temporal processing can be divided into four aspects [7]: temporal resolution, temporal ordering, temporal masking, and temporal integration. One aspect of temporal processing that has been extensively studied in children with SLI is temporal resolution. Temporal resolution is defined as the minimum time interval necessary for a subject to distinguish between distinct acoustic events [8].

Tallal and Piercy [9] were amongst the first researchers to investigate temporal resolution and temporal ordering in children with and without SLI. They did so by measuring their capacity to discriminate and repeat sequences of two or more tones of different frequencies. The authors showed that the performance of children with SLI worsened significantly as compared to children without SLI when the time interval between the two tones was diminished. In this regard, Tallal [10,11] suggested that a perceptual deficit related to auditory temporal processing underlies the language difficulties observed in children with SLI. According to this author, children with SLI show a particular difficulty for the processing of auditory information that is rapidly presented or for the processing of brief acoustic signals. Thus, SLI may have a non-linguistic perceptual basis [9–11]. Evidence in favour of this claim is provided by a study of Benasich and Tallal [12]. The authors carried out a longitudinal study in children with and without a family history of language disorder. They

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demonstrated that the threshold for rapid auditory processing at 7.5 months of age was the single best predictor of language outcome at the age of 2 years. At the age of 3 years, rapid auditory processing threshold and being male, together predicted 39–41% of the variance in language outcome.

From a similar perspective, McArthur and Bishop [13] proposed that poor auditory processing generates unstable representations of spoken sounds, leading to difficulty in perceiving and producing language. This hypothesis has been investigated by a number of other authors [e.g. 14–16]. An important aspect that should be taken into consideration is that most studies investigating the association between auditory temporal processing and language outcomes in children with SLI have used behavioural tasks that normally depend on nonsensory processing such as working memory. In these tasks, a listener typically must attend to and remember the ordering of sequentially presented sounds and then indicate which of the sounds had a distinguishing feature [17]. Importantly, a number of studies have shown that children with SLI have immediate memory deficits relating to working memory and short-term memory capacities and that these deficits may contribute to their language problems [18–22]. Thus, previous research may have observed a nonsensory-driven deficit in temporal processing tasks, rather than a primary auditory deficit. Consequently, it may be hypothesized that children with SLI demonstrate a poorer performance on auditory temporal processing tasks than children without SLI due to a deficit in short-term memory and working memory, and not due to a primary auditory dysfunction. To address this issue, the aim of this study was to compare the performance of children with and without SLI on a temporal processing task controlling for the confounding of verbal immediate memory, including short-term memory and working memory.

2. Methods

2.1. Subjects

A purposive sample of 60 children with and without SLI was selected for research purposes. The SLI group was comprised of 30 children aged between 6.0 years and 6 years 11 months, with an average age of 6 years 3 months. Nine children were female and 21 male. The control group was comprised of 30 children with typical language development, matched to the SLI group for gender and age (+/−6 months). The age range for the control group was the same as for the group of children with SLI, with an average age of 6 years 2 months.

Children with SLI were selected from the kindergarten and first-grade classes of 10 special schools and 7 mainstream schools from the Metropolitan Region of Santiago de Chile. These places were contacted as they were known to have students with a diagnosis of SLI. Children with typical language development were selected from the kindergarten and first-grade classes of mainstream schools in the Metropolitan Region of Santiago de Chile.

School officials provided prior authorization for the study, and the parents of participating children provided a signed informed consent form. Approval from the Ethics Committee of the Faculty of Medicine, University of Chile was obtained prior the commencement of the study.

2.2. Sample selection

To select the children for both groups (SLI and typical language development), the school files of students were reviewed to determine the ages and presence/absence of a diagnosis of SLI of potential study participants. Children younger than 6 years of age or older than 6 years, 11 months were excluded. For each SLI child selected (see below for further details about selection procedures), a gender- and age (+/−6 months) matched-control child with typical language development was selected using the same procedures as for the SLI group.

Following the pre-selection process based on children's ages and presence or absence of a diagnosis of SLI, children's parents were contacted to invite them to participate in the study. Oral and written information regarding the study's aims and procedures was provided to each parent. Those parents who consented to allow their children to participate in the study signed an informed consent form. Following consent, the parents filled out a questionnaire to collect data necessary to confirm that the child had an SLI (for the SLI group) or that they had a typical language development (for the control group). Children from either group were excluded if they presented with history of neurological or emotional disorders, or recurrent middle-ear problems.

Selected children based on the parents' questionnaire were scheduled for two evaluation sessions before inclusion in the final sample. The first session took place at the children's school and the second one at the Audiology Laboratory of the Department of Speech and Hearing Sciences, University of Chile (Santiago, Chile). The following procedures were carried out in a quiet room at children's school.

2.2.1. Test of Early Language Development (Third Edition) – Spanish (TELD-3: S) [23]

This test includes expressive (37 items) and receptive (39 items) language subtests and evaluates the semantic, syntactic, and morphological aspects of language. The manual provides norms for children aged 2–7 years. The results are obtained as raw scores which are then converted to quotients for expressive language, receptive language, and overall spoken language, which is a general indicator of the child's language ability. These values were used to classify children's language performance as: very high (quotient of 131–165), high (quotient of 121–130), above average (quotient of 111–120), average (quotient of 90–110), below average (quotient of 80–89), poor (quotient of 70–79), or very poor (quotient of 35–69). The inclusion criterion for participants in the SLI group was poor or very poor overall language performance. The inclusion criterion for participants with typical language development (control group) was normal language performance; thus below-average to very high performance for both the expressive and receptive subtests.

2.2.2. Test of Nonverbal Intelligence (TONI 2) [24]

This test is a standardized instrument that uses abstract figures to measure problem-solving ability. This tool is free of cultural and language factors and can be applied individually or collectively in subjects aged 5–85 years. The test provides nonverbal instructions and does not require fine motor skills. The content is abstract and the responses do not require specific knowledge or information. The inclusion criterion for children in both the SLI and the typical language development groups was normal performance on the non-verbal cognitive evaluation (a score above the 10th percentile for their chronological age).

The following procedures were carried out in one session at the Laboratory of Audiology, Faculty of Medicine, University of Chile.

2.2.3. Otoscopy

An otoscope (Heine 2000) was used to observe the external auditory canal and tympanic membrane, bilaterally. Selected participants from both groups (SLI and control) should present with an absence of obstruction in the external auditory canal and absence of abnormalities of the tympanic membrane, bilaterally.

2.2.4. Tympanometry

A tympanometer (Otometrics Madsen Zodiac 901) was used to evaluate middle-ear function. Selected participants from both groups (SLI and control) should present with Jerger type A results, bilaterally.

2.2.5. Pure tone audiometry

Using an audiometer (Interacoustics AC40) and TDH-34 headphones calibrated with the audiometer, air conduction audiometric thresholds were obtained for frequencies 500, 1000, 2000, and 4000 Hz. All selected subjects from both groups should obtain hearing thresholds equal or below 15 dB HL for each frequency tested, bilaterally.

Selected children based on the procedures mentioned above continued with data collection procedures as explained below.

2.3. Data collection

The following procedures were carried out in all selected participants from both groups, SLI ($n = 30$) and typical language development (control group, $n = 30$). All procedures were carried out in one session at the Laboratory of Audiology, Faculty of Medicine, University of Chile.

2.3.1. Adaptive Test of Temporal Resolution (ATTR) [25]

This procedure was used to evaluate temporal resolution, an aspect of temporal processing. The software for this test was installed in an Acer Aspire 3620 laptop computer. The test was run and presented to each participant directly from the computer with Memorex NC100 headphones. The ATTR is comprised of four gap detection tests, differentiated by the stimuli used to define the gap. In this research, a test with narrow-band noise (NBN) and a within-channel gap detection paradigm was utilized. The stimuli consisted of quarter-octave NBN, centred on 2 kHz, before and after the gap. Stimuli were binaurally presented, at the highest comfortable loudness level for the subject. The test uses an adaptive procedure with a 2-down/1-up stepping rule to target 70.7% correct gap detection [25]. Gap durations are presented in integer steps of 1 ms. Once eight reversals had occurred, the test stopped automatically and a gap detection threshold (GDT, in milliseconds) was calculated. Arithmetic and geometric GDTs are provided by the software. The geometric mean of the GDT was used in further comparative analysis between groups, as it is less affected by large variations in the adaptive track. The paradigm utilized was a standard two-alternative forced-choice (S-2AFC) procedure. A reference sound with no gap was presented, followed by two more sounds, one of which contained a gap. Each child was required to select which of the two sounds following the reference one, was different. As soon as each sound was played, a box appeared on the computer screen. The child was required to indicate on the box corresponding to the different sound. Oral instructions were given to each child by the examiner. Practice items were provided before the commencement of the test.

2.3.2. Wechsler Intelligence Scale for Children, digit span forward and digit span backward subtests – Third Edition, Chilean version (WISC III v.ch) [26]

These subtests are designed to evaluate immediate memory for auditory stimuli in children aged 6–16 years. The two subtests are series of digits repeated forward or backward after being read out loud by the examiner at a rate of one digit per second. Digit span forward has been considered as a measure of short-term memory [e.g. 19,27] whereas digit span backward has been considered as a measure of working memory [e.g. 19]. The series for digit span forward are 3–9 digits, and the series for digit span backward are 2–8 digits. Each child was instructed to pay attention to the numbers that the examiner spoke before repeating them in the same order (digit span forward), or in reverse order (digit span backward). Two trials were performed for each sequence, beginning with a sequence of 2 digits that the child had to repeat back in the same order. The test was stopped when the child failed both attempts for a given span. Results were recorded as the longest span of digits that the child was able to repeat, even if only one of the two attempts was correct.

2.4. Data analysis

Data were analyzed with SPSS v.17 [28] and R [29–31]. Mann–Whitney tests were initially computed to determine possible significant differences between children with and without SLI for ATTR results and digit span forward and backward. Subsequently, two analyses of covariance (ANCOVA) were used to determine whether there was a significant difference for ATTR results (temporal resolution) between the two groups (SLI and typical language development) when controlling for short-term memory (digit span forward, Model 1) and working memory capacity (digit span backward, Model 2), respectively. Finally, Spearman's correlation coefficient between ATTR results and the digit span subtests of the Wechsler scale were computed. The correlation analysis was performed separately for the two groups (SLI and typical language development).

3. Results

3.1. Group differences for temporal processing and immediate memory outcomes

Figs. 1 and 2 show means and confidence intervals results for the ATTR and the Wechsler digit span subtests for both groups (SLI and typical language development). Children with SLI ($n = 30$) showed higher variability for the distribution of ATTR results than those with typical language development ($n = 30$). In addition, children with SLI performed significantly worse than children with typical language development for ATTR ($Z = 2.16$, $p = 0.03$), digit

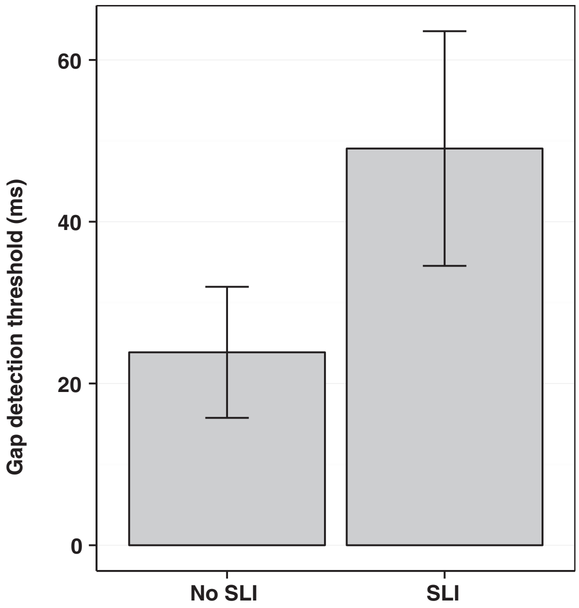

Fig. 1. Barplot of the scores of SLI children ($n = 30$) and children without SLI ($n = 30$) for the Auditory Test of Temporal Resolution (ATTR) results. Scores are in milliseconds. SLI. Children with Specific Language Impairment. No SLI. Children with typical language development. Bars represent group means. Error bars represent the confidence interval (95%) for each group.

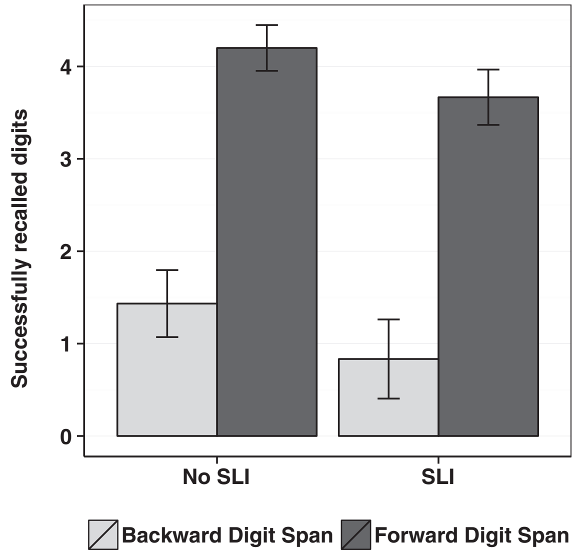

Fig. 2. Barplot of the scores of SLI children ($n = 30$) and children without SLI ($n = 30$) for forward digit span and backward digit span results. Scores are in number of digits correctly recalled. Children with Specific Language Impairment coded as SLI, children with typical language development coded as No SLI. Bars represent group means. Error bars represent the confidence interval (95%) for each group.

span forward ($Z = 2.59$, $p = 0.009$), and digit span backward ($Z = -2.05$, $p = 0.04$).

3.2. Between-group differences for temporal processing performance controlling for the confounding of immediate memory

Analyses of covariance were used to compare ATTR results between the groups of children with SLI and with typical language development. Two independent models were constructed. In Model 1, short-term memory (results for the digit span forward test) was included in the analysis as a covariate. In Model 2, working memory (results for the digit span backward test) was included in the analysis as a covariate. Before conducting the ANCOVA tests, the sample was inspected for outliers and assumptions were tested. Four cases were deemed as influential based on Studentized Residuals and Cook's Distance. Subsequently, assumptions about homoscedasticity were inspected by conducting a Breusch–Pagan heteroscedasticity tests on each model and a Bartlett Test between groups on the dependent variable. Results for all tests were statistically significant ($p < 0.001$). Since homoscedasticity was not met, the ANCOVA tests for both models were conducted by calculating parameters using the Restricted Maximum Likelihood (REML) method instead of the Ordinary Least Squares method and by allowing variances to differ between groups. Following Gałecki and Burzykowski [32], these steps compensate for the violation of the homoscedasticity assumption.

Results of the REML estimation for Model 1 were statistically significant both for the digit span forward covariate ($b = -5.48$, $p = 0.03$) and for the group factor ($b = 20.6$, $p < 0.001$). In addition, a Log-Likelihood ratio test was obtained by comparing an REML homogeneous-variance ANCOVA model against an REML heterogeneous-variance ANCOVA model, mainly to gauge whether the stratified variance improved the overall fit. The chi-squared value for this Log-Likelihood ratio test was significant ($p < 0.001$), which suggests that allowing variances to differ between groups does improve fit. As for Model 2, results of the REML estimation were statistically significant only for the group factor ($b = 23.85$, $p < 0.001$), digit span backward covariate's coefficient not being statistically significant. As was the case with Model 1, a Log-Likelihood ratio test comparing an homogeneous-variance model against an heterogeneous-variance model was also statistically significant ($p < 0.001$), which again suggests an improvement in fit.

Finally, since the sample consisted of children and since one group belongs to a clinical population, a non-parametric bootstrap simulation was conducted to ensure that the found effects were not sample-specific and that their interpretation is indeed aligned with targeted populations. Boostrap simulation was conducted with 10,000 repetitions and bias-corrected accelerated (BCa) confidence intervals were obtained for regressors' coefficients [33].

As shown in Table 1, results are consistent with reported results for the ANCOVA tests (confidence intervals do not include 0 except for the digit span backward covariate in Model 2, which reflects the non-significant value of the same covariate in that model)

3.3. Correlations

Spearman's correlation coefficient was used to evaluate a possible association between ATTR results and Wechsler digit span results. Both groups of subjects (SLI and typical language development) were analyzed separately. For the SLI group ($n = 28$), a statistically significant correlation between ATTR results and digit span forward (Rho = −0.48, $p = 0.009$) was found. This indicates that the lower (i.e., the better) the value for the ATTR gap detection threshold in milliseconds, the longer (i.e., the better) the digit span. No significant correlation between ATTR results and digit span backward (Rho = −0.36, $p = 0.05$) was found for the SLI group. In addition, no significant correlations ($p = 0.05$) among test results for the group of children with typical language development ($n = 28$) were found.

4. Discussion

4.1. Differences between children with SLI and children with typical language development for temporal resolution and immediate memory tasks

The results of this study showed statistically significant differences between children with SLI and those with typical language development for short-term memory, working memory as well as temporal resolution. Regarding short-term memory, Conti-Ramsden [27] reported significant differences between a group of children with SLI and a control group for a digit recall task similar to the one used in this research. In addition, other studies have found that short-term memory is impaired in children with SLI, especially for tasks requiring the repetition of unfamiliar phonological forms [34–41]. Similarly, previous studies have also shown that children with SLI present with decrements in working memory as observed in this study [19,42–44].

Table 1
Results of non-parametric boostrap simulations for Model 1 and Model 2, 10,000 repetitions each.

Regressor	Original parameter	Bias	CI (lower)	CI (upper)
Model 1				
Digit span forward	−11.09	−0.08	−17.37	−2.77
Group	−17.85	−0.01	7.2	30.85
Model 2				
Digit span backward	−3.18	0.13	−8.57	2.81
Group	21.57	0.18	10.51	34.01

Note that no confidence intervals (CI) for regressors' coefficients include zero, except for digit span backward in Model 2.

In terms of auditory temporal resolution, many studies have shown that children with SLI perform significantly worse than their peers without language impairment on temporal processing tasks [14,45]. Wright et al. [14] found that a group of subjects with SLI showed significantly poorer performance, as compared to a control group matched for age and non-verbal intelligence, on a detection task of temporally masked, brief sounds. The SLI group mainly showed difficulty in identifying tones in a backward masking condition (when the tone was presented prior to the masking noise). The authors attributed this finding to a temporal resolution deficit. In addition, Ahmmed et al. [45] found statistically significant differences between children with and without SLI for a within-channel gap detection task, similar to the one used in this study, using stimuli centred at 4000 Hz.

4.2. Association between immediate memory and temporal processing capacity in children with SLI

The aim of this study was to determine whether differences in temporal processing capacity between children with SLI and children without SLI, reported in previous studies, may be due to the confounding of nonsensory processing, specifically immediate memory capacity. Therefore, analyses of covariance (ANCOVA) were carried out in order to determine the role of immediate memory in the observed reduced temporal processing abilities in SLI children. The two models of ANCOVA showed significant differences for auditory gap detection thresholds (ATTR results) between groups, even when controlling for short-term memory (measured as digit span forward) and working memory (measured as digit span backward) capacities. Also, short-term memory was significantly associated with ATTR results. In addition, the stratified correlation analysis showed that short-term memory scores were correlated with ATTR results only in the group of children with SLI. Based on these results, we reject the hypothesis that nonsensory processing, or at least immediate memory as evaluated in this study, underlies differences for auditory temporal processing between children with and without SLI.

However, a question about the correlation between short-term memory and temporal resolution capacity in SLI children, a pattern that was not observed in typical language development children, remains. Similarly, a recent study [46] did not find a correlation between digit span forward and the gaps-in-noise test, which is a similar procedure to the one used in this study to evaluate temporal resolution, in children with normal language development. We hypothesize that two aspects may relate to this significant correlation observed only in SLI children. Firstly, SLI children presented with a poorer performance in immediate memory capacity than children without SLI. Thus, when the performance on a task, such as detection of gaps, requires the use of immediate memory resources and these resources are more limited than expected, they become more crucial to successfully complete the task. Therefore, the more limited immediate memory resources, the poorer the performance on tasks that require the use of immediate memory. Second, children with SLI may present a primary auditory deficit characterized by poor temporal processing abilities. This deficit relates to an inefficient processing of auditory information leading to a poor representation of auditory stimuli throughout the auditory system. Therefore, cognitive resources such as immediate memory become more important as the individual must interpret cortical representations of incoming auditory stimuli that have been partially processed within the auditory system. This is similar to the scenario when a listener has to process speech sounds in a challenging acoustic scenario such as in the presence of background noise. In this context, part of the acoustic information of stimuli is lost and thus more cognitive effort must be allocated to successfully process the remaining acoustic information of incoming stimuli. A recent study [47] supports this hypothesis. The authors have shown that a correlation between auditory working memory and language comprehension tasks in school-aged children without SLI was stronger when language tasks were presented in the presence of background noise. The authors suggested that this relates to an increase contribution of working memory. Therefore, we suggest that children with SLI in this study, as a group may have presented with a decrement in sensory processing of auditory information, as evaluated by the temporal resolution task, and due to such deficit they required an additional contribution of nonsensory processing such as immediate memory to complete the task.

Evidence from previous studies, using objective measures of temporal resolution which do not depend on immediate memory capacity support the hypothesis that SLI children present with a primary auditory deficit relating to temporal processing. Marler and Champlin [48] reported delayed wave V latency of the auditory evoked potential in children with SLI when the stimulus (tone burst) was followed by a masking noise (backward masking). These deficits were not observed in the group of children without SLI. Oram Cardy et al. [49] used magnetoencephalography (M50, M100) to study evoked neural activity to two 40 ms tones passively presented in rapid succession in a group of subjects with SLI and a group with typical language development. The results showed that significantly fewer M50 responses to the second tone were identified in children with SLI as compared to those with typical language development. This finding supports the hypothesis that children with SLI show a temporal processing impairment that is independent of immediate memory deficits.

Finally, despite group differences between children with and without SLI for temporal processing, it is not possible to establish the role of auditory temporal processing in the pathogenesis of SLI. Further research should be conducted to establish the importance of auditory temporal processing deficits in SLI and how temporal processing therapy may help to improve the language deficits observed in children with SLI.

In conclusion, the results of this study (a) demonstrate an association between poor temporal resolution performance and the presence of SLI, although a cause–effect association cannot be assumed, and (b) show that immediate memory deficits alone, as evaluated through forward and backward digit span, cannot explain the temporal resolution impairment observed in children with SLI.

5. Limitations of this study and suggestions for further research

One of the main limitations of this study was the use of digit span as the sole procedure to evaluate immediate memory capacity. As discussed above, a number of other instruments have been used in previous research to evaluate both short-term and working memory, including the use of language-based tools such as the repetition of nonwords. In addition, other nonsensory processing aspects beyond immediate memory have not been included in this research. Finally, temporal processing was evaluated with only one task that included a within-channel paradigm of gap detection. Paradigms including between-channel gap detection as well as other aspects of temporal processing such as temporal ordering and temporal masking should be utilized in further studies with the aim to comprehensively evaluate temporal processing. Therefore, we suggest that the results of this study should be taken with caution. As explained above, other nonsensory aspects, not evaluated in this research, may relate to the lower performance amongst SLI children for temporal processing. In addition, immediate memory was not comprehensively measured and thus different results could be found if tasks using different types of stimuli are used. Also, a within-channel gap detection task is relatively easier than a between-channel gap detection task. Therefore, for the latter a stronger influence of nonsensory processing amongst SLI children may be observed.

Finally, future research in this area should consider the use of both behavioural and nonbehavioural measures of auditory temporal resolution. In this way, the contribution of nonsensory processing in temporal processing tasks can be better controlled.

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