Relationship between sensitivity to temporal fine structure and spoken language abilities in children with mild-to-moderate sensorineural hearing loss

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Abstract

Children with sensorineural hearing loss show considerable variability in spoken language outcomes. We tested whether specific deficits in supra-threshold auditory perception might contribute to this variability. In a previous study [Halliday, Rosen, Tuomainen, & Calcus, (2019), *J. Acoust. Soc. Am, 146,* 4299], children with mild-to-moderate sensorineural hearing loss (MMHL) were shown to perform more poorly than normally hearing (NH) controls on measures designed to assess sensitivity to the temporal fine structure (TFS, the rapid oscillations in the amplitude of narrowband signals over short time intervals). However, they performed within normal limits on measures assessing sensitivity to the envelope (E; the slow fluctuations in the overall amplitude). Here, individual differences in unaided sensitivity to TFS accounted for significant variance in the spoken language abilities of children with MMHL, after controlling for nonverbal IQ, family history of language difficulties, and hearing loss severity. Aided sensitivity to TFS and E cues was equally important for children with MMHL, whereas for children with NH, E cues were more important. These findings suggest that deficits in TFS perception may contribute to the variability in spoken language outcomes in children with sensorineural hearing loss.

Keywords: sensorineural hearing loss; hearing impairment; auditory perception; language development; temporal fine structure; envelope

I. INTRODUCTION

Auditory perception plays a fundamental role in language development. The acoustic components of speech are known to convey important linguistic information. Like any complex auditory signal, speech signals are decomposed by the auditory system into an array of overlapping frequency bands. The resulting narrowband signals are decomposed further into at least two temporal fluctuation rates (Poeppel et al., 2008; Rosen, 1992). The envelope (E) comprises the slow oscillations (2-50 Hz) in the overall amplitude of a narrowband auditory signal, and is evident in the acoustic properties of intensity, amplitude modulation (AM), and the rise (onset) and fall (offset) times of sounds (Rosen, 1992). In contrast, temporal fine structure (TFS) comprises the rapid oscilliations (0.6-10 kHz) in the amplitude of a narrowband signal over short time intervals (< 1 s), and carries information about the frequency content of a sound, including the formant spectra of speech (Rosen, 1992; Smith et al., 2002). For those with normal hearing (NH), the E has been argued to play a crucial role in the comprehension of speech in quiet (Drullman, 1995; Shannon et al., 1995; Smith et al., 2002; Xu et al., 2017; Zeng et al., 2004). In turn, sensitivity to E cues has been proposed to contribute to language development in children with NH (Goswami, 2019). Indeed, such is the importance of E cues that children with severe-to-profound sensorineural hearing loss who wear cochlear implants - which provide poor access to TFS cues - can still acquire oral language (Tomblin et al., 1999). However, for children with mild-to-moderate sensorineural hearing loss (MMHL), who typically wear hearing aids and not cochlear implants, the perception of the acoustic cues of speech is also likely to be degraded, albeit to a lesser extent. The current study asked whether the auditory perception of TFS and E cues was associated with language development in children with MMHL, compared to those with NH.

The role of E cues in the acquisition of phonological representations and in learning to read has long been argued for children with NH (e.g., Goswami et al., 2002). For example, children with dyslexia have been shown to perform more poorly than normal readers on tasks assessing sensitivity to the sound E, including AM detection, rise time discrimination, and rhythm perception

(for review, see Goswami, 2011), as well as neural correlates of E encoding (De Vos et al., 2017; Hämäläinen et al., 2008; Power et al., 2016). Moreover, individual differences in sensitivity to these acoustic features have been shown to be predictive of concurrent and longitudinal reading abilities (Goswami et al., 2002; Goswami et al., 2012; c.f. Rosen, 2003). However, more recently it has been argued that sensitivity to E cues may also play a role in the acquisition of spoken language (for review, see Goswami, 2019). Consistent with this view, deficits in sensitivity to rise time, sound duration, and rhythm perception have been found in children with specific language impairment (SLI; now known as developmental language disorder or DLD; Corriveau et al., 2007; Corriveau and Goswami, 2009). Recently, sensitivity to rise time at 7 and 10 months was shown to be predicted by vocabulary, but not phonological processing skills, at 3 years of age (Kalashnikova et al., 2019).

In contrast to the literature on children with NH, the role of auditory perception in the language development of children with sensorineural hearing loss has received somewhat less attention. This is perhaps surprising, because we have known for many years that sensorineural hearing loss is associated with abnormal performance on psychoacoustic tasks (for a review, see Moore, 2007; Tomblin et al., 2014). For example, individuals with sensorineural hearing loss have been shown to exhibit poorer frequency selectivity (i.e. a reduced ability to resolve the spectral components of a complex sound), owing to a broadening of auditory filters (Peters and Moore, 1992; Rance et al., 2004). In addition, sensorineural hearing loss has been linked to reduced sensitivity to TFS, evidenced by the poorer performance of both adults and children with MMHL on tasks such as frequency discrimination, fundamental frequency (F0) discrimination, and frequency modulation detection (Halliday and Bishop, 2006; Henry and Heinz, 2013; Moore, 2014; Rance et al., 2004). However, sensorineural hearing loss appears to leave E processing relatively intact, as demonstrated by the normal or enhanced performance of adults and children with MMHL on tasks such as AM detection (e.g. Rance et al., 2004; Wallaert et al., 2017).

There is increasing evidence that these changes in auditory perception may contribute to the poorer speech discrimination abilities of individuals with sensorineural hearing loss. In hearing-aid users, positive correlations between frequency selectivity and speech perception have been found (Davies-Venn et al., 2015; Dreschler and Plomp, 1985; Henry et al., 2005), although not consistently (Hopkins and Moore, 2011; Rance et al., 2004; Summers et al., 2013; Ter Keurs et al., 1993). More consistent have been reports of correlations between measures of TFS perception and speech perception in quiet and noise, which have been demonstrated in both children and adults with MMHL (adults: Hopkins and Moore, 2011; Johannesen et al., 2016; Mehraei et al., 2014; Papakonstantinou et al., 2011; Summers et al., 2013; children: Rance et al., 2004). Importantly, impaired sensitivity to TFS has been argued to play a critical role in the speech-in-noise perception difficulties of adults with sensorineural hearing loss, by interfering with their ability to "listen in the dips" of the background noise (Hopkins et al., 2008; Lorenzi et al., 2006; Swaminathan and Heinz, 2012). Given the role of speech perception in the acquisition of spoken language (Tsao et al., 2004), individual variability in TFS processing may contribute to the variable language outcomes seen in children with sensorineural hearing loss.

Several large-scale studies have assessed the speech and language development of children with sensorineural hearing loss in recent years. A consistent finding from these studies is that of a large degree of variability in the spoken language outcomes of these children. A number of demographic factors have been identified that appear to contribute to this variability, including severity of hearing loss (Ching et al., 2013; Tomblin et al., 2015; Wake et al., 2004, 2005), age of detection and/or age of first fitting of cochlear implants or hearing aids (Ching et al., 2013; Wake et al., 2005; Yoshinaga-Itano et al., 1998), and hearing device audibility, quality, and use (McCreery et al., 2015; Tomblin et al., 2014, 2015). In addition, some studies have suggested a possible role for genetic predisposition to co-occurring language disorders in those children with sensorineural hearing loss who show particular weaknesses in language acquisition (Gilbertson and Kamhi, 1995; Halliday et al., 2017a). However, a key finding is that these factors do not appear to fully account

for the extent of variability in language outcomes experienced by this group. To our knowledge, the possibility that specific deficits in auditory perception might contribute to this variability has not yet been examined.

A series of previous studies assessed the auditory perceptual and language abilities of forty-six 8-16-year-old children with MMHL and 44 age-matched NH controls (Halliday et al., 2019, 2017a, 2017b). Auditory psychophysical thresholds were obtained on a battery of tasks, including those designed to assess sensitivity to the TFS (frequency discrimination and detection of modulations in the F0), and E (rise time discrimination and AM detection) of simple and complex sounds. To assess the mediating role of amplification on auditory perception, children with MMHL were tested both while they were wearing their hearing aids and while they were not. For both hearing-aid conditions, the MMHL group performed more poorly than NH controls on the two psychophysical tasks designed to measure sensitivity to TFS (Halliday et al., 2019). However, performance on the two measures of E processing did not differ between groups. The same children with MMHL also showed poorer and more variable performance than controls on a variety of measures of spoken language but not reading (Halliday et al., 2017a). However, to date, the relationship between sensitivity to E and TFS cues and individual differences in language abilities, both spoken and reading, has not been assessed.

The current study examined whether performance on these behavioural measures of TFS and E processing was linked to the spoken or written language abilities of these same groups of children with MMHL and NH controls. Based on previous findings for children (Rance et al., 2004), and adults (e.g. Lorenzi et al., 2006) with sensorineural hearing loss, it was predicted that unaided sensitivity to TFS would correlate with, and significantly account for a proportion of the variance in, the spoken language (but not reading) abilities of children with MMHL. Based on evidence from children with NH (Goswami, 2019), it was hypothesized that sensitivity to E cues would play a greater role in the spoken language and reading abilities of controls. Finally, this study also examined whether aided sensitivity to TFS or E cues was more important in accounting for

individual differences in the language abilities of children with MMHL. Because hearing aids increase the audibility of important components of speech, one possibility was that the relationship between aided thresholds and language would be similar to that of NH controls. Alternatively, because the MMHL group still showed deficits in sensitivity to TFS cues even when they were wearing their hearing aids (Halliday et al., 2019), it was possible that the relationship between aided thresholds and language would be the same as for the unaided condition.

II. METHODS

Audiometric, psychophysical, and psychometric testing took place at University College London (UCL) over two sessions, each lasting around 90 minutes, and separated by at least a week. Each child was tested by a single experimenter. Audiometric and psychophysical testing was conducted in a sound-attenuated booth, whereas psychometric testing was conducted in an adjacent quiet room. The parents/guardians of all participants completed an in-house questionnaire concerning their child's demographic, developmental, and medical background. The project received ethical approval from the University College London (UCL) Research Ethics Committee, and informed written consent was obtained from the parent/guardian of each child.

A. Participants

Forty-six children with MMHL (27 boys, 19 girls; MM group) and 44 age-matched NH controls (19 boys; 25 girls; NH group) participated in this study (see Table I). Children were aged 8-16 years-old at the time of testing, and children in the NH group were age-matched to within 6 months to at least one child in the MM group. All children were from monolingual English-speaking backgrounds and all communicated solely via the oral/aural modality (i.e. they did not use sign language, as is typical for children with MMHL). Non-verbal IQ was measured for all participants using the Block Design subtest of the Wechsler Abbreviated Scale of Intelligence (WASI; Wechsler, 1999). All had non-verbal IQ scores within the normal range (IQ-equivalent standard scores of ≥ 85, equivalent to T-scores ≥ 40), although scores were significantly higher for the NH group than the MM group (see Table I). Maternal education level (age in years at which

the mother left full-time education) was used as a proxy for socio-economic status and did not differ significantly between groups. Finally, family history of language difficulties was scored bimodally as either having, or not having, a first-degree relative (parent or sibling) with a childhood history of spoken or written language difficulties unrelated to a hearing loss. Family history of language difficulties did not differ between groups.

Unaided pure-tone air-conduction thresholds were obtained for both ears for all children using an Interacoustics AC33 audiometer with Telephonics TDH-39 headphones (see Figure 1). For the MM group, 19 children were identified as having mild hearing loss, and 27 as moderate hearing loss, where mild was defined as a better-ear pure-tone-average (BEPTA) audiometric threshold of 21-40 dB HL across octave frequencies 0.25-4 kHz, and moderate as a BEPTA threshold of 41-70 dB HL (British Society of Audiology, 2011). Children with NH had mean audiometric thresholds of ≤ 20 dB HL across the octave frequencies for both ears, and thresholds of ≤ 25 dB HL at any particular frequency. For the MM group, age of detection of hearing loss ranged from 2 months to 14 years (median = 57 months), although in all cases, the hearing loss was thought to be congenital and could not be attributed to a syndrome or neurological impairment (including auditory neuropathy spectrum disorder), or any known post-natal event (e.g. measles). Forty-three of the MM group were fitted with bilateral prescription hearing aids, although one child was refusing to wear their aids. Age of first hearing aid fitting was from 3 months to 15 years (median = 65 months).

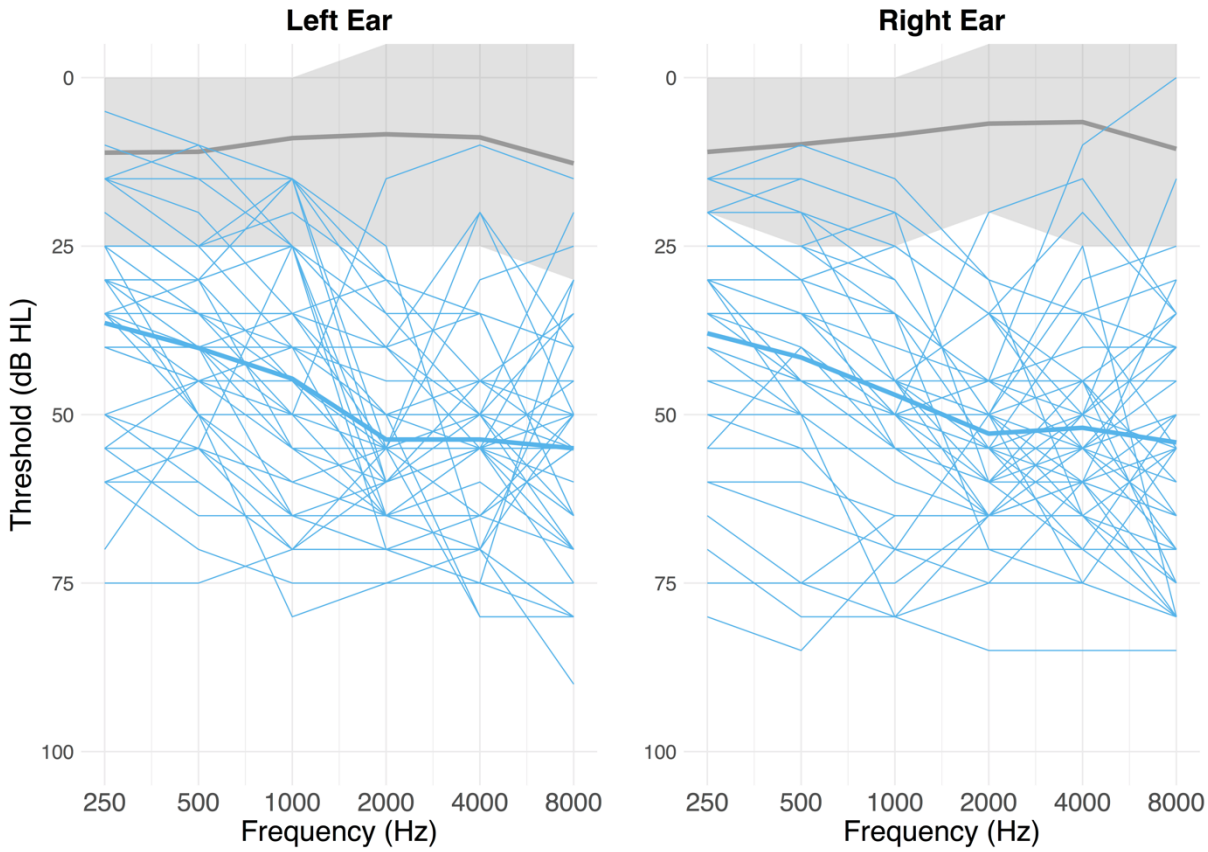

Figure 1: Individual (thin blue lines) and mean (thick blue lines) air-conduction pure-tone audiometric thresholds for the MM group, for the left and right ears. Mean thresholds for the NH group are also shown (thick grey line), along with the range for the NH group (shaded grey area).

B. Auditory processing tests

Auditory processing was assessed using four psychophysical tasks. TFS is thought to carry information about both the frequency of sinusoidal stimuli and the F0 of complex stimuli, for carriers below 4–5 kHz (Hopkins et al., 2008; Moore and Ernst, 2012). Therefore, sensitivity to TFS was assessed using a frequency discrimination (FD) task for a 1-kHz sinusoid, and a F0 modulation detection task for a complex harmonic sound (Moore and Ernst, 2012; Moore and Gockel, 2011). In contrast, the E carries information about the slow fluctuations (between 2-50 Hz) in the amplitude of an auditory signal. Thus, sensitivity to E cues was assessed using a rise time (RT) discrimination task for a 1-kHz sinusoid, and a slow-rate (2-Hz) AM detection (AMD) task for a complex harmonic sound.

1. Stimuli

For each task, a continuum of stimuli was created, ranging from a fixed, repeated standard sound to a maximum, variable, deviant sound. All stimuli were 500 ms in duration, and were root-mean-square (rms)-normalised for intensity. All were ramped on and off with a 15-ms linear ramp, apart from the RT task (see below).

For the FD task, the target sounds were generated with frequency differences spaced in the ratio of $1/\sqrt{2}$ downwards from a starting point of 1.5 kHz. Detection of modulation in F0 (F0 task) was assessed using a complex harmonic carrier generated by passing a waveform containing 50 equal-amplitude harmonics (at a F0 of 100 Hz) through three simple resonators. The resonators were centred at 500, 1500, and 2500 Hz with a 100 Hz-bandwidth. The F0 was modulated at 4 Hz. For target stimuli, the depth of modulation varied from $\pm$0.16 Hz to $\pm$16 Hz in logarithmic steps.

For the RT task, the on-ramp of the target sounds ranged logarithmically from 15 ms (the standard) to 435 ms (the maximal deviant) across 100 stimuli, whereas off-ramps were fixed at 50 ms. For the AMD task, the standard stimulus was unmodulated and identical to that used in the F0 task. Deviant stimuli for this task were amplitude modulated at a rate of 2 Hz, with modulation depth ranging from 80% to 5% across 100 stimuli in logarithmic steps.

Stimuli were presented free-field, in a sound-attenuating booth, at a fixed sound pressure level of 70 dB SPL, via a single speaker that was positioned facing the child approximately one metre away from their head.

2. Psychophysical procedure

The auditory processing tasks were delivered in a computer-game format and responses were recorded via a touch-screen. A three-interval, three-alternative forced-choice (3I-3AFC) procedure was used. On each trial, participants were presented with three sounds, each represented on the screen by a different cartoon character and separated by a silent 500-ms inter-stimulus interval. Two of the sounds were the same (standard) sound, and one was a different (deviant) sound. Children were instructed to select the "odd-one-out" by pressing the character that "made

the different sound". For all tasks, an initial one-down, one-up rule was used to adapt the task difficulty until the first reversal. Subsequently, a three-down one-up procedure was used, targeting 79.4% correct on the psychometric function (Levitt, 1971). The step size decreased over the first three reversals and then remained constant.

For the FD task, the frequency difference between the standard and the deviant was initially 50% (i.e. 1 kHz vs. 1.5 kHz). The initial step size was equivalent to a factor of 0.5, reduced to $1/\sqrt{2}$ after the first reversal. For the F0 task, the difference in modulation depth of the F0 between the standard and the deviant was initially ±16 Hz. The step size was initially 12 steps along the continuum, which reduced to four after the first reversal. For the RT task, difference in rise time between the standard and deviant was initially 420 ms. The initial step size was 12 steps along the continuum, reducing to six after the first reversal. Finally, for the AMD task, the initial difference in amplitude modulation depth was 80%. The initial step size was 21 stimulus steps along the continuum, reducing to seven after the first reversal.

For all tasks, tracks terminated after 50 trials, or after four reversals had been achieved (whichever came first). Children were required to repeat a run if their threshold was at ceiling (0.3 % of runs for the NH group, 2.1 % for the MM group), or if they had achieved fewer than four reversals at the final step size (1.1 % of runs for the NH group, 0.9 % for the MM group). In these cases, the repeated run was used to estimate threshold. Participants were given unlimited time to respond and visual feedback was provided after each response. Participants undertook a minimum of five practice trials for each task, where they were asked to discriminate between the endpoints of each continuum (i.e. the easiest discrimination). Participants were required to achieve a ratio of at least 4/5 correct practice trials before testing began, with a maximum of 15 practice trials per task.

Each child completed two runs per task, separated across two sessions. For the children with MMHL who wore hearing aids, one run was completed whilst they were wearing their hearing aids (aided condition), and another when they were not (unaided condition). Hearing aids were set

to the children's usual settings for aided testing. The order of tasks and conditions was counter-balanced between children.

3. Threshold calculations and auditory composite thresholds

For each task, thresholds were calculated as the mean value of the target stimulus at the last four reversals for each adaptive track, equivalent to the geometric mean. Psychophysical thresholds were log-transformed (base 10) to normalise the data. Normalised thresholds for children with MMHL were then age-transformed against the thresholds of the NH group to provide an age-standardised threshold (M = 0; SD = 1). Sensitivity to TFS and E was calculated separately for the MM and NH groups as the arithmetic mean age-standardised thresholds for the FD and F0 tasks (TFS composite) and for the RT and AMD tasks (E composite), respectively. Composite thresholds were calculated for both aided and unaided conditions for children with MMHL who wore hearing aids (n = 42). For each composite threshold, a higher number corresponded to poorer performance.

C. Language tasks

Language abilities were assessed using a battery of seven standardised psychometric tests, the majority of which had been recently standardised using UK norms (the exception being repetition of nonsense words; see below). Children with MMHL who normally wore hearing aids did so during psychometric testing, using their standard hearing aid settings. For all tests except repetition of nonsense words (see below), scores were converted to z scores ($M = 0$, $SD = 1$) based on the age-normed standardised scores of each individual test. Spoken language skills were assessed using receptive and expressive vocabulary tests, receptive and expressive grammar tests, as well as a test evaluating phonological processing and memory. Reading skills were assessed using word reading and pseudoword decoding tests.

1. *Standardized language tests*

Spoken language receptive vocabulary was assessed using the British Picture Vocabulary Scale 3rd Edition (BPVS; (Dunn and Dunn, 2009). For this test, children were presented with four pictures

on each trial, and required to select the one that best illustrated the meaning of a word said by the experimenter. Expressive vocabulary was assessed using the Expressive Vocabulary (for children aged 8-9 years) and Word Definitions (for children aged ≥ 10 years) subtests of the Clinical Evaluation of Language Fundamentals (CELF) 4th UK Edition (Semel et al., 2006), respectively. For the Expressive Vocabulary subtest, children were shown a series of pictures, and for each one asked to say a word that best corresponded to the picture. For the Word Definitions subtest, the experimenter would say a word, and then use that word in a sentence. Children were required to define each target word.

Receptive grammar was assessed using a computerized version of the Test for the Reception of Grammar (TROG; Bishop, 2003), which assesses understanding of 20 different grammatical contrasts. Children were presented on each trial with four pictures, and a sentence that was spoken by a female native Southern British English speaker via the speaker of a laptop. The task was to select the picture that best depicted the spoken target sentence from the remaining three foil pictures that depicted sentences that were altered in grammatical/lexical structure. Expressive grammar was assessed using the Recalling Sentences subtest of the CELF (Semel et al., 2006). For this test, sentences of increasing length and complexity were spoken by a different female native Southern British English speaker and presented via the laptop speaker. Children were asked to repeat back each sentence verbatim.

Phonological processing and memory was assessed using the Repetition of Nonsense Words subtest from the neuropsychological assessment NEPSY (Korkman et al., 1998). The thirteen original nonword items from this subtest were re-recorded by a female native speaker of Southern British English and presented via a computer at a comfortable listening level. Nonwords ranged from two to five syllables in length, and the child's task was to repeat each nonword out loud. Responses were recorded and marked offline. Because the norms for the NEPSY only go up to 12 years, 11 months, z-scores were calculated for this test from the age-normed scores for the NH group.

Reading abilities were assessed using the Word Reading and Pseudoword Decoding subtests of the Wechsler Individual Achievement Test (WIAT, Wechsler, 2005). For both tests, children were presented with a series of written words or pseudowords and asked to read them out loud as accurately as possible, in their own time.

2. *Language composite scores*

Scores on the spoken language and reading individual tests were combined to form two composite language measures: a spoken language composite measure, and a reading composite measure. The spoken language composite measure was calculated as the mean age-standardized score for each child based on the z scores obtained for the five different spoken language tests of receptive and expressive vocabulary, receptive and expressive grammar, and phonological processing and memory. The reading composite measure was calculated as the mean standardized score for each child based on the z scores obtained for the two reading tests. Each composite score was therefore equivalent to the mean age-standardised score for each child across the spoken language and reading measures, expressed as a z-score ($M = 0$; $SD = 1$).

D. Missing data

It was not possible to obtain a pure-tone average threshold for one child in the NH group owing to poor compliance with the test protocol. For this child, a screening procedure confirmed normal hearing, and the child's audiometric thresholds were not included in the study. One child with MMHL was unable to complete the auditory processing tasks in the unaided condition. Thresholds for this child were therefore included for the aided condition only. Thresholds on the RT task were not obtained for six children with MMHL in the unaided condition and one in the aided condition, owing to failure to pass the practice trials and/or fewer than four reversals being achieved at the final step size. RT thresholds for these children were therefore not included and composite E thresholds calculated from the AMD task only. Questionnaire data recording the age at which the mother left full-time education was missing for five participants (four MM, one NH).

All missing data were examined and it was deemed unlikely that the data were missing at random. Therefore, missing data was not replaced.

E. Data analysis

Data were analysed using linear mixed models because of missing data in some conditions. Analyses were conducted using RStudio version 1.2.1578 (RStudio Team, 2019) and R version 3.6.1 (R Core Team, 2019). Utilized packages included LME4 (Bates et al., 2015) and ggplot2 (Wickham et al., 2016) packages.

III. RESULTS

A. Auditory processing and language measures

Composite TFS and E thresholds for the NH and MM groups (unaided and aided conditions) are shown in Figure 2. To assess whether the groups differed in their auditory processing thresholds, two linear mixed models were run, fitting unaided thresholds for the MM and NH groups (unaided condition), and aided and unaided thresholds for the MM and NH groups respectively (aided condition). For each condition, auditory processing (TFS vs E) and group (MM vs NH), along with their interaction, were included as fixed factors, and participants were included as random effects. For the unaided condition, the effects of group and auditory processing were not significant [$\beta = 0.29$, $t(125.60) = 1.27$, $p = .206$; and $\beta = 1.60e\text{-}15$, $t(87) = 0$, $p > .999$, respectively]. However, there was a significant group x auditory processing interaction [$\beta = 1.24$, $t(87) = 6.20$, $p < .001$]. For the aided condition, while the effect of group was not significant [$\beta = -0.28$, $t(124.61) = -1.25$, $p = .212$], the effect of auditory processing was [$\beta = 0.77$, $t(84) = 5.37$, $p < .001$], as was the group x auditory processing interaction [$\beta = -0.77$, $t(84) = -3.84$, $p < .001$]. In both the unaided and aided conditions, independent samples *t*-tests (Welsh) confirmed that the interactions were due to the MM group obtaining higher (poorer) thresholds on the TFS composite relative to controls [unaided: $t(70.20) = -6.46$, 95% CI [-2.0, - 1.1], $p < .001$, $r = 0.61$; aided: $t(66.24) = -4.46$, 95% CI [-1.52, -0.58], $p < .001$, $r = 0.48$], but not on the E composite [unaided: $t(82.43) =$

-1.33, 95% CI [-0.73, 0.14], p = .188, r = 0.14; aided: t(80.60) = -1.32, 95% CI [-0.70, 0.14], p = .191, r = 0.15].

To assess whether the performance of children in the MM group differed between the unaided and aided conditions, a linear mixed effects model was run with auditory processing (TFS vs E) and condition (aided vs unaided) along with their interaction as fixed factors, and participants as random effects. The effect of auditory processing was significant, [β = 0.77, t(124.35) = 4.04 , p < .001], but the effect of condition was not [β = 0.02, t(126.45) = 0.11, p =.914], and the condition x auditory processing interaction just missed significance [β = 0.47, t(124.35) = 1.76 , p = .081]. Post-hoc exploration (paired-samples t-tests) of the marginally non-significant interaction indicated that thresholds were lower (better) in the aided compared to the unaided condition for TFS, [t(40) = 2.92, 95% CI [0.16, 0.89], p = .006, r = .42], but not for E, [t(40) = -0.03, 95% CI [-0.39, 0.38], p = .977, r = .00] for children with MMHL who wore hearing aids.

Composite spoken language and reading scores for the NH and MM groups are shown in Figure 3. A linear mixed model, with language modality (spoken vs reading) and group (NH vs MM) plus their interaction as fixed factors, and participants as random effects, revealed significant effects of both language modality and group [β = -0.24, t(88) = 2.81, p = .006, and β = -1.12, t(120.42) = -7.55, p < .001, respectively] as well as a significant modality x group interaction [β = 0.70, t(88) = 5.87, p < .001]. Welch two-sample t-tests showed that the MM group performed more poorly than the NH group on both the spoken language and reading measures [difference for spoken scores = 1.12, 95% CI [0.82, 1.43], t(80) = 7.34, p < .001, r = .63; difference for reading scores = 0.42, 95% CI [0.14, 0.71], t(87) = 2.96, p = .004, r = .30]. However, paired-samples t-tests showed that whereas the NH group exhibited significantly lower scores for reading than for spoken language [difference = 0.24, 95% CI [0.08, 0.40], t(43) = 2.95, p = .005, r = .41], the MM group showed the opposite pattern [difference = -0.46, 95% CI [-0.64, -0.29], t(45) = -5.31, p < .001, r = .62].

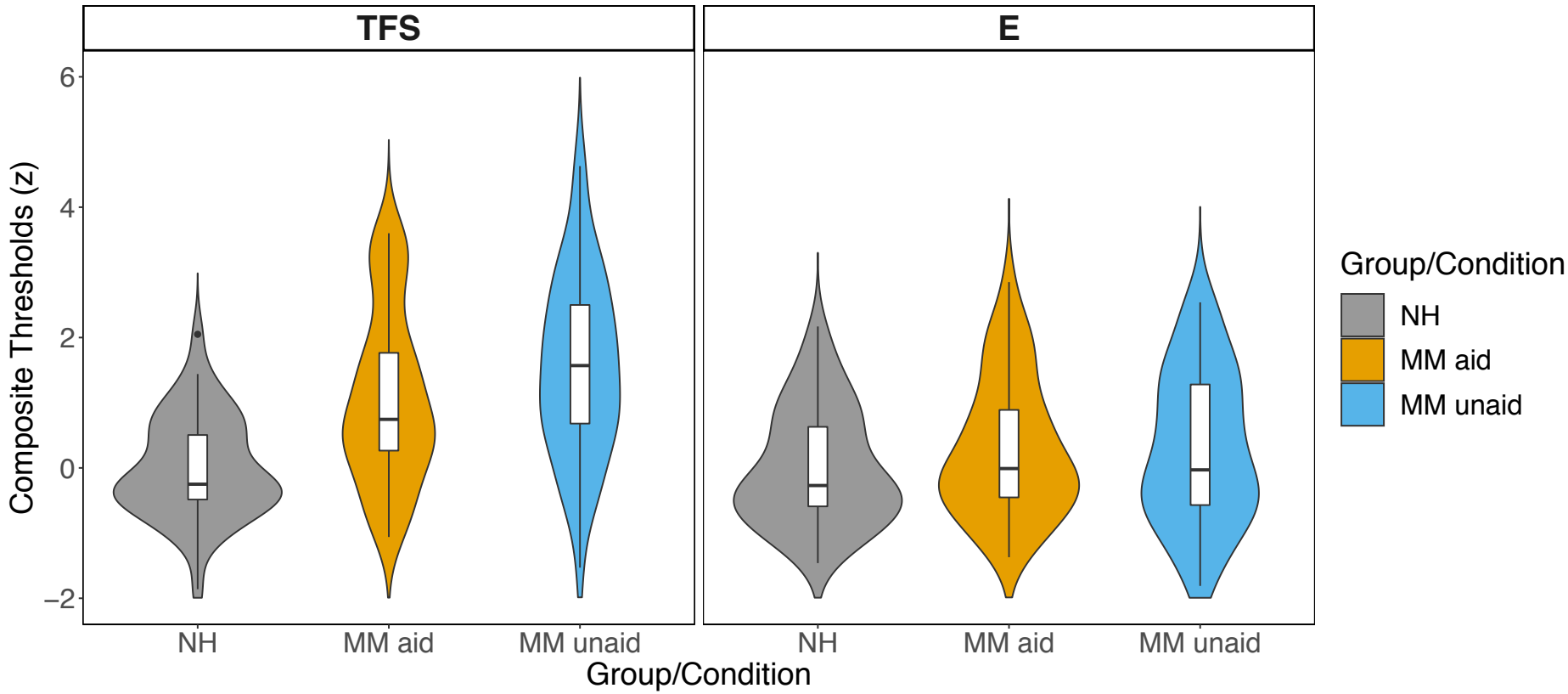

Figure 2. Performance on the TFS and E composite measures for the NH in grey (TFS: *M* =0, *SD* = 0.78; E: *M* = 0, *SD* =0.89), aided MM in orange (TFS: *M* = 1.53, *SD* = 1.37; E: *M* = 0.29, *SD* = 1.16), and MM unaided in blue (TFS: *M* =1.05, *SD* =1.32; E: *M* = 0.28, *SD* =1.05). Higher thresholds correspond to poorer performance. Boxplots represent the 25th, 50th and 75th percentile for each group/condition while the violin plots illustrate kernel probability density, i.e. the width of the violin area represents the proportion of the data located there.

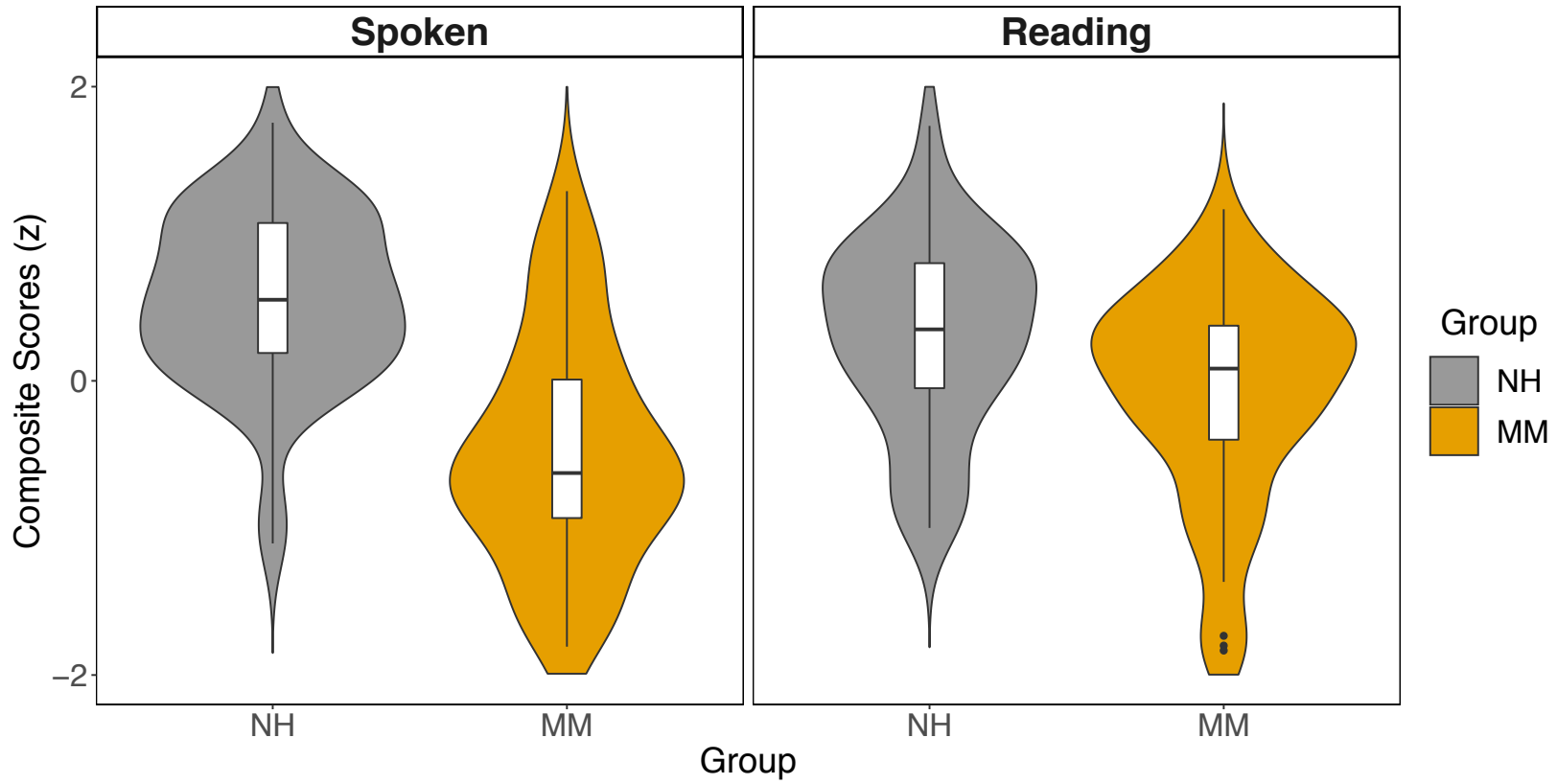

Figure 3. Performance on the Spoken Language and Reading composite measures for the NH in grey (Spoken: *M* = 0.56, *SD* = 0.59; Reading: *M* = 0.32, *SD* = 0.63) and MM in orange (Spoken: *M* = -0.56, *SD* = 0.85; Reading: *M* = -0.1, *SD* = 0.72). Higher thresholds correspond to poorer performance. Boxplots represent the 25th, 50th and 75th percentile for each group/condition while the violin plots illustrate kernel probability density, i.e. the width of the violin area represents the proportion of the data located there. The circles indicate outliers that were ± 1.5 times the inter-quartile range (difference between the 25th and 75th percentile).

B. Relationship between auditory processing and language measures

To explore the relationship between the auditory processing and language measures, two-tailed Pearson's correlations were conducted between the TFS and E composite thresholds and spoken language and reading composite scores (see Figure 4). Correlations were examined separately for the NH and MM groups, and for the unaided and aided conditions for the MM group. Relationships with other known audiological (unaided BEPTA thresholds, a measure of severity of hearing loss), demographic (maternal education, a measure of socio-economic status), and cognitive (nonverbal IQ) predictors of language were also examined. Significance levels were adjusted to control for multiple comparisons, with Bonferroni-corrections applied at a family-wise level (i.e. for comparisons between auditory versus language scores and between the other known predictors versus language scores; both $\alpha = .004$).

For the MM group, there was a significant correlation between unaided TFS composite thresholds and spoken language composite scores [$r(45) = -.46$, 95% CI [-.66, -.19], $p = .002$]. Lower (better) unaided TFS thresholds were associated with higher (better) spoken language scores. In addition, there was a marginally significant correlation between aided E composite thresholds and spoken language scores [$r(42) = -.43$, 95% CI [-.65, -.15], $p = .004$], with better E thresholds being associated with better spoken language. Finally, for the MM group, higher nonverbal IQ was associated with higher spoken language and reading scores [$r(46) = .54$, 95% CI [.29, .72], $p < .001$; and $r(46) = .54$, 95% CI [.29, .72], $p < .001$, respectively]. None of the other correlations between the auditory processing versus language composite scores or between the other known predictors and language scores reached significance for the MM group after correcting for multiple comparisons.

For the NH group, a slightly different pattern was observed. After controlling for multiple comparisons, both E composite thresholds and TFS composite thresholds were significantly correlated with spoken language composite scores [$r(44) = -.50$, 95% CI [-.69, -.24], $p < .001$, and $r(44) = -.43$, 95% CI [-.65, -.16], $p = .003$, respectively]. Lower (better) auditory processing

thresholds were associated with higher (better) spoken language scores. In addition, higher maternal education was significantly associated with better spoken language scores [$r(43) = .52$, 95% CI [.26, .71], $p < .001$]. None of the other correlations between language (spoken or reading) and auditory processing or other known predictors reached significance for the NH group after controlling for multiple comparisons.

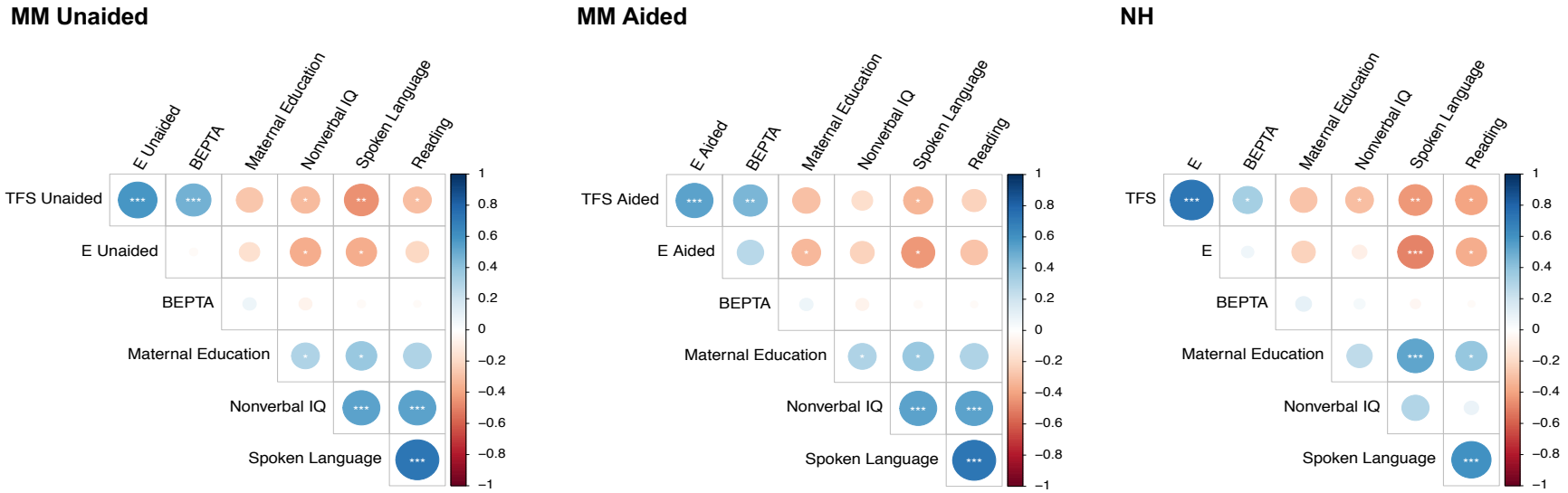

Figure 4. Correlograms representing the correlation coefficients between the auditory processing, language, BETPA, demographic, and cognitive variables (from positive, blue, to negative coefficients, red) for the HL group (unaided and aided conditions) and the NH group. Positive correlations are displayed in blue and negative correlations in red. Color intensity and the size of the circle are proportional to the correlation coefficients. *p* values are shown *** $p < .001$, ** $p < .004$, * $p < .05$.

C. Modelling of language scores

To assess whether sensitivity to TFS or E cues contributed to the variance in spoken language and/or reading abilities over and above other known predictors of language, a series of multi-level linear models was run, for the MM group (unaided and aided conditions) and NH group separately. Four generic models were used. In Model 1, BEPTA thresholds, nonverbal IQ, maternal education levels, and family history of language/reading difficulties were entered into the model as fixed effects, with participants as random effects. In Model 2, TFS composite thresholds were added to Model 1 to investigate whether TFS processing made an independent contribution to the dependent variables. In Model 3, E composite thresholds were added to Model 1 to investigate whether E processing made an independent contribution to the dependent variables. Finally, in Model 4, both TFS and E composite thresholds were added to Model 1. Analysis of variance (ANOVA) was used to determine the best fitting model for each group (MM and NH), condition (unaided and aided), and dependent variable (spoken language and reading). For each analysis, see supplementary material at [*URL will be inserted by AIP*] for Table IV summarizing model comparisons and Figures 5, 6 and 7 representing the effect of each independent variable on spoken language scores for the best models.

Table II shows the estimates of the best fitting models for each group and condition for the spoken language composite measure. For the MM group in the unaided condition, adding TFS composite thresholds (Model 2) significantly improved Model 1 (likelihood-ratio test (LRT) = 10.08, $p = .002$), whereas adding E composite thresholds failed to improve either Model 1 (Model 3; LRT = 3.67, $p = .056$), or Model 2 (Model 4; LRT = 0.001, $p = .970$). As shown in Table II, for the MM group for the unaided condition, a significant amount of the variance in spoken language scores was accounted for by individual variance in nonverbal IQ, family history of language difficulties, and unaided TFS composite thresholds, but not by BEPTA thresholds, maternal education levels, or E thresholds.

For the MM group for the aided condition, a slightly different pattern of results was observed for spoken language. Aided TFS thresholds (Model 2) also significantly improved Model 1 (LRT = 6.36, p = .012), but so did aided E thresholds (Model 3, LRT = 7.27, p = .007). However, adding both aided TFS and aided E thresholds (Model 4) did not significantly improve Model 2 (LRT = 3.55, p = .059), or Model 3 (LRT = 2.64, p = .104). For this condition therefore, variance in spoken language scores was significantly and independently accounted for by nonverbal IQ, family history of language difficulties, and either aided TFS or aided E thresholds (but not both; see Table II).

For the NH group, the best fitting model for spoken language was Model 3. Adding TFS (Model 2) did not improve the fit of Model 1 (LRT = 2.77, p = .096), whereas adding E (Model 3) did (LRT = 9.40, p = .002). Adding E to Model 2 also significant improved the fit (Model 4; LRT = 7.11, p = .008), but adding TFS to Model 3 did not (LRT = 0.48, p = .487), suggesting that only E thresholds made a significant contribution to the model fit. The estimates of the final best model are shown Table II, and suggest that maternal education levels and E composite thresholds both made significant, independent contributions to the variability in spoken language scores for the NH group, whereas BEPTA thresholds, nonverbal IQ, and family history of language difficulties did not.

Finally, the estimates of the best fitting models for the reading composite measure are shown in Table III. For the MM group, adding TFS or E thresholds failed to improve Model 1 for either the unaided or aided conditions. The same was true for the NH group. The final models indicated that nonverbal IQ and family history of language difficulties contributed significantly to reading scores for the MM group, whereas maternal education only contributed in children with NH.

IV. DISCUSSION

The primary goal of the present study was to examine whether sensitivity to the TFS or E of sounds was associated with language outcomes in children with sensorineural hearing loss. In

addition, the study examined whether these relationships were the same for children with NH, and for children with hearing loss while they were wearing their hearing aids, and while they were not. As sensorineural hearing loss is associated with reduced sensitivity to TFS but not E cues (Buss et al., 2004; Hopkins and Moore, 2011; Lorenzi et al., 2006), it was hypothesised that TFS, but not E sensitivity, would be associated with the spoken language (but less so reading) abilities of children with MMHL. For children with NH, it was hypothesised that sensitivity to E (but not TFS) cues would relate to both spoken language and reading abilities (Goswami, 2019; Kalashnikova et al., 2019).

Our first hypothesis was supported by data from the unaided condition, in which sensitivity to TFS and E cues was measured for children with MMHL while they were not wearing their hearing aids. It is important to note that unaided BEPTA thresholds were significantly correlated with TFS thresholds, suggesting that elevated TFS thresholds were associated with worsening cochlear damage. However, the models showed that unaided TFS thresholds significantly contributed to the variance in spoken language (but not reading) scores for children with hearing loss, even after BEPTA thresholds and other predictors of language had been controlled for. In contrast, unaided sensitivity to E cues did not improve the model fit for spoken language scores in this condition. Our findings therefore suggest that deficits in TFS processing may relate to poorer spoken language outcomes for children with MMHL, over and above conventional measures such as unaided BEPTA thresholds. This is consistent with previous studies, with adults with hearing loss showing significant correlations between speech recognition scores and frequency modulation detection at 1000 Hz when audibility (BEPTA) was statistically controlled for (Buss et al., 2004).

The direction and nature of this relationship remains to be determined. One possibility is that the unaided TFS thresholds were reflective of the extent of cochlear damage experienced by the children with MMHL. However, it is also possible that these findings demonstrate a relationship between TFS perception and language development per se in children with

sensorineural hearing loss. This relationship may be direct, with reduced sensitivity to TFS leading to poorer perception of both the F0 and formants of speech, with subsequent consequences for spoken language acquisition. Indeed, speech perception is a known predictor of spoken language development both in children with NH (Tsao et al., 2004; Ziegler et al., 2005) and in those with hearing loss (Blamey et al., 2001; Davidson et al., 2011). Alternatively, the relationship may be more indirect, via impaired speech in noise perception. To that end, previous research in adults has shown that sensorineural hearing loss-induced deficits in sensitivity to TFS cues may limit the ability to utilise periods of quiet ("dips") in a background noise for accurate speech perception (Ardoint and Lorenzi, 2010; Hopkins et al., 2008; Hopkins and Moore, 2010; Lorenzi et al., 2006; Summers et al., 2013). For children with hearing loss, it is plausible that this decreased ability to listen to speech in background noise plays a specific role in hindering the acquisition of spoken language. Consistent with this idea, speech perception in noise has been shown to be particularly problematic for children with sensorineural hearing loss (Goldsworthy and Markle, 2019), and associated with vocabulary development in this group (Klein et al., 2017; McCreery et al., 2019; Walker et al., 2019). Given that much spoken language learning occurs in suboptimal, noisy environments (Dockrell and Shield, 2006), it may be that deficits in TFS perception negatively impact upon this process for children with hearing loss, by impairing their ability to perceive speech under such conditions.

The present analyses showed a slightly different pattern of results when children with MMHL wore their hearing aids for the auditory tasks. In this, aided condition, either sensitivity to TFS or sensitivity to the E - but not both – significantly improved the model for spoken language scores after controlling for the other predictors. A possible explanation for these findings is that our results may simply reflect an improvement in the audibility of stimuli in the aided compared to the unaided condition. Indeed, whilst hearing aids would not have provided additional TFS cues, the increased sensation level is likely to have contributed to the improvement in aided TFS thresholds relative to unaided TFS thresholds in the current study (see also Wier et al., 1977).

Aided audibility has been shown to significantly contribute to the speech and language outcomes of children with sensorineural hearing loss, over and above other known predictors for this group (McCreery et al., 2015, 2019; Tomblin et al., 2015). For instance, a recent, large cohort study indicated that variability in spoken language abilities for 8-10-year-old children with mild-to-severe sensorineural hearing loss was moderated by an interaction between BEPTA thresholds and aided hearing levels (Tomblin et al., 2020). Moreover, higher daily use of hearing aids has been associated with better listening comprehension, but not vocabulary, reading, or morphological awareness, in children with mild hearing loss aged between 9 and 11 years (Walker et al., 2020). Aided audibility was not measured in the present study, so its possible relations with language for children with hearing loss cannot be assessed here. However, a relationship between aided audibility and speech perception has not consistently been found in children with sensorineural hearing loss (Klein et al., 2017), raising the possibility that other factors may also play a role.

One such factor may be that specific aspects of aided auditory perception also impact upon the spoken language development of children with sensorineural hearing loss who wear hearing aids. In this respect, the wearing of hearing aids appeared to make the results of children with MMHL more similar to those of NH controls. For children with NH, E composite thresholds significantly contributed to the variance in spoken language abilities, whereas TFS thresholds did not. In contrast, children with MMHL in the aided condition resembled both children with NH, and themselves in the unaided condition, in terms of their pattern of results. Thus, it is possible that where TFS sensitivity is normal (as for children with NH), sensitivity to E cues may be related to spoken language abilities, by contributing to the syllabic and prosodic (stress) representation of the speech signal (see Kalashnikova et al,. 2019). However, where TFS is degraded, as is the case for children with hearing loss, this may place an upper limit on the utility of E cues in contributing to spoken language outcomes. Nevertheless, E thresholds did contribute to the variance in spoken language outcomes in the aided condition for children with hearing loss, suggesting that these cues may still play a role when TFS cues are more audible. Alternatively, it may be that those children

who showed greater deficits in unaided TFS perception were able to benefit more from the enhancement of E cues in the aided condition. Further research is needed to determine whether improvements in the aided perception of TFS and E cues contribute to the better language outcomes of children with hearing loss who wear hearing aids, and whether this relationship is mediated by aided audibility (see Tomblin et al., 2014, 2015, 2020).

While auditory processing skills significantly improved the models for spoken language for the different groups and conditions, this was not the case for reading, contrary to our hypothesis for the NH group. Previous studies have reported a relationship between sensitivity to E cues and reading in children with NH, particularly for those with dyslexia (Goswami, 2019; Goswami et al., 2002). The current results for children with NH showing no reading difficulties, did not reveal such relationship. It is possible that the two tests used to assess reading skills in this study were not sufficient, or fine-grained enough, to observe a link between auditory perception and reading in children with NH, or that a such relationship is stronger for children with dyslexia. Alternatively, it is possible that reading abilities are not directly related to the E and TFS tasks used here, or that other mechanisms mediate this relationship (Rosen, 2003). Lastly, it may be that the children in the current study were too old for such a relationship to be observed, which may well be expected to lessen as children get older and the reciprocal relationship between spoken language and reading acquisition takes hold (Ricketts et al., 2020). Whatever the reason, it is of interest that the children with MMHL in the current study showed both normal E processing and generally normal reading abilities. Therefore, it appears that for children with MMHL at least, sensitivity to TFS may better relate to spoken language development than it does to learning to read (see also Halliday and Bishop, 2005, for similar results regarding a lack of relationship between frequency discrimination and reading for children with MMHL).

The current study had a number of limitations that ought to be considered. First, while the auditory tasks were designed to be predominantly reliant upon sensitivity to TFS and E cues (Halliday et al., 2019), it remains possible that other auditory processes were involved. For instance,

for the TFS tasks it is difficult to rule out the possible impact of reduced frequency selectivity due to broader auditory filters in the hearing loss group (Oxenham et al., 2009). It is therefore possible that the findings reflect an added effect of both TFS and frequency selectivity on language outcomes in children with sensorineural hearing loss. Second, owing to equipment failure it was not possible to measure hearing aid fit or aided audibility for the children with MMHL. It is therefore possible that the hearing aids of the hearing loss group were not optimally fitted, or were not functioning optimally on the day of testing, and so did not provide sufficient auditory input during the aided tasks. Further research is therefore needed to investigate the role of aided audibility on the abilities of children with sensorineural hearing loss who wear hearing aids to process the auditory temporal modulations of speech. Third, the present study included a single sample of children with MMHL. Future research is needed to replicate these findings. Finally, the current study employed a cross-sectional design, which limits the ability to infer causal relationships between auditory perception and language outcomes. Longitudinal designs are therefore needed to investigate the causal direction of the relationship between auditory perception and language in children with sensorineural hearing loss.

V. CONCLUSIONS

Children with mild-to-moderate (MMHL) present with deficits in the processing of the fastest temporal modulations of sounds, the temporal fine structure (TFS), and show generally poorer language outcomes than their normally hearing (NH) peers. The present study indicated that the auditory processing of temporal modulations may play a role in the spoken language development of children with MMHL, and also children with NH. We found that unaided sensitivity to the TFS of sounds contributed to variance in the spoken language abilities of children with MMHL, and that measures of TFS sensitivity were more related to spoken language than pure-tone audiometry in this group. When children with MMHL used their hearing aids for the auditory tasks, aided sensitivity to either the TFS or envelope (E) of sounds (but not both) contributed to the spoken language variability of the same group of children. Finally, for children with NH, sensitivity to E

cues (but not TFS) was a better predictor of spoken language abilities. We suggest that the poorer spoken language abilities of children with sensorineural hearing loss may in part be a consequence of their reduced sensitivity to TFS, which may lead to poorer speech perception, particularly in noise. In contrast, for children with NH, or those with hearing loss who are wearing their hearing aids, sensitivity to E cues may play a more important role. Thus, children with sensorineural hearing loss who show greater deficits in TFS perception may be at greater risk of spoken language difficulties than those with better TFS perception. TFS sensitivity may therefore be a useful measure to investigate individual variability in spoken language outcomes for children with sensorineural hearing loss. Further research is needed to better understand the potential role of aided audibility in mediating this relationship.

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4

TABLE I. Mean (SD) and ratio participant characteristics for the NH and MM groups and between-groups comparisons.

Variable[a]	NH (N = 44)	MM (N = 46)	*t*	*df*	*p*	*r*/OR	95% CI
Age (years)	11.54 (2.05)	11.44 (2.16)	0.23	88	.821	0.02	-0.78, 0.98
BEPTA thresholds (dB HL)	**7.33 (3.95)**	**43.37 (12.01)**	**-19.28**	**55**	**<.001**	**0.93**	**-39.79, -32.30**
Maternal education (years)	20.47 (2.89)	19.33 (2.65)	1.88	83	.063	0.20	-0.06, 2.33
Non-verbal IQ (T-score)	**60.64 (8.48)**	**55.63 (8.71)**	**2.76**	**88**	**.007**	**0.28**	**1.40, 8.61**
Family history (0:1)	35:9	35:11	---	1	.802	1.22	0.45, 3.32

a. NH = normally hearing group; MM = mild-to-moderate hearing loss group; OR = odds ratio; CI = confidence interval; BEPTA = better-ear pure-tone average thresholds. Parametric tests were two-sample Welsh t-tests; Non-parametric tests were Fisher's Exact Test.

TABLE II. Best fitting multi-level linear models for spoken language composite scores for the MM group for the unaided and aided conditions, and for the NH group. Significant parameters ($p < .05$) are in boldface.

Model/ Predictors	Estimate	SE	*df*	*t*	*p*
MM group-unaided					
Intercept	**-3.06**	**1.04**	**35**	**-2.94**	**.006**
BEPTA	0.02	0.01	35	1.54	.132
Maternal education	0.03	0.04	35	0.69	.494
Nonverbal IQ	**0.03**	**0.01**	**35**	**2.66**	**.012**
Family history	**-0.56**	**0.25**	**35**	**-2.27**	**.030**
TFS unaided (Model 2)	**-0.28**	**0.09**	**35**	**-3.12**	**.004**
MM group-aided					
Intercept	**-3.05**	**1.16**	**32**	**-2.65**	**.013**
BEPTA	0.01	0.01	32	1.07	.293
Maternal education	0.00	0.05	32	0.07	.948
Nonverbal IQ	**0.04**	**0.01**	**32**	**3.05**	**.005**
Family history	**-0.65**	**0.28**	**32**	**-2.37**	**.024**
TFS unaided (Model 2)[a]	**-0.25**	**0.10**	**32**	**-2.41**	**.022**
E aided (Model 3) [a]	**-0.32**	**0.12**	**32**	**-2.60**	**.014**
NH group					
Intercept	-1.06	0.68	36	-1.55	.130
BEPTA	-0.02	0.02	36	-0.99	.329
Maternal education	**0.08**	**0.02**	**36**	**3.13**	**.003**
Nonverbal IQ	0.00	0.01	36	0.47	.639
Family history	**-0.38**	**0.17**	**36**	**-2.18**	**.036**
E (Model 3)	**-0.25**	**0.08**	**36**	**-3.01**	**.005**

[a] Models 2 and 3 both fit the data better than Model 1 for the MM group in the aided condition, but could not be distinguished from one another. For simplicity, we report the full model for Model 2 (aided TFS), and the specific additional contribution made by aided E for Model 3.

TABLE III. Summary of Model 1 for reading scores for the MM group for the unaided condition, and for the NH group. Significant parameters ($p < .05$) are in boldface.

Model/ Predictors	Estimate	SE	*df*	*t*	*p*
MM group-unaided[a]					
Intercept	**-2.64**	**0.94**	**36**	**-2.82**	**.008**
BEPTA	0.00	0.01	36	0.21	.833
Maternal education	0.02	0.04	36	0.43	.669
Nonverbal IQ	**0.04**	**0.01**	**36**	**3.61**	**.001**
Family history	**-0.59**	**0.23**	**36**	**-2.54**	**.016**
NH group					
Intercept	-0.69	0.94	37	-0.73	.472
BEPTA	-0.01	0.02	37	-0.45	.659
Maternal education	**0.08**	**0.03**	**37**	**2.33**	**.025**
Nonverbal IQ	-0.01	0.01	37	-0.68	.503
Family history	-0.11	0.24	37	-0.45	.659

[a] *Note.* The best fitting models for the MM group were similar for the unaided and aided conditions; therefore only the final unaided model is shown here.

Supplementary Material:

Table IV. Model comparisons for the four different models for the MM group for the unaided and aided conditions, and the NH group for the unaided condition, for the spoken language and reading composite scores. The best fitting models are in boldface. *$p < .05$; **$p < .01$.

Group	Condition	Outcome	Model	LL	AIC	Likelihood-ratio test (LRT)			
						Model 2 vs 1	Model 3 vs 1	Model 4 vs 2	Model 4 vs 3
MM	Unaided	Spoken language	1	-42.06	98.12				
			2	**-37.02**	**90.04**	**10.08****			
			3	-40.23	96.45		3.67		
			4	-37.02	92.04			0.001	6.41*
		Reading	**1**	**-35.46**	**84.91**				
			2	-34.69	85.38	1.53			
			3	-35.42	86.84		0.07		
			4	-34.47	86.93			0.44	1.90
	Aided	Spoken language	1	-40.25	94.51				
			2	**-37.08**	**90.15**	**6.36***			
			3	**-36.62**	**89.24**		**7.27****		
			4	-35.30	88.60			3.55	2.64
		Reading	**1**	**81.89**	**-33.95**				
			2	80.97	-32.48	2.93			
			3	82.06	-33.03		1.83		
			4	82.46	-32.23			0.50	1.60
NH	Unaided	Spoken language	1	66.37	-26.19				
			2	65.60	-24.80	2.77			
			3	**58.97**	**-21.49**		**9.40****		
			4	60.49	-21.25			7.11**	0.49
		Reading	**1**	**85.49**	**-33.74**				
			2	83.89	-33.94	3.60			
			3	84.56	-34.28		2.92		
			4	85.61	-33.8			0.28	0.96

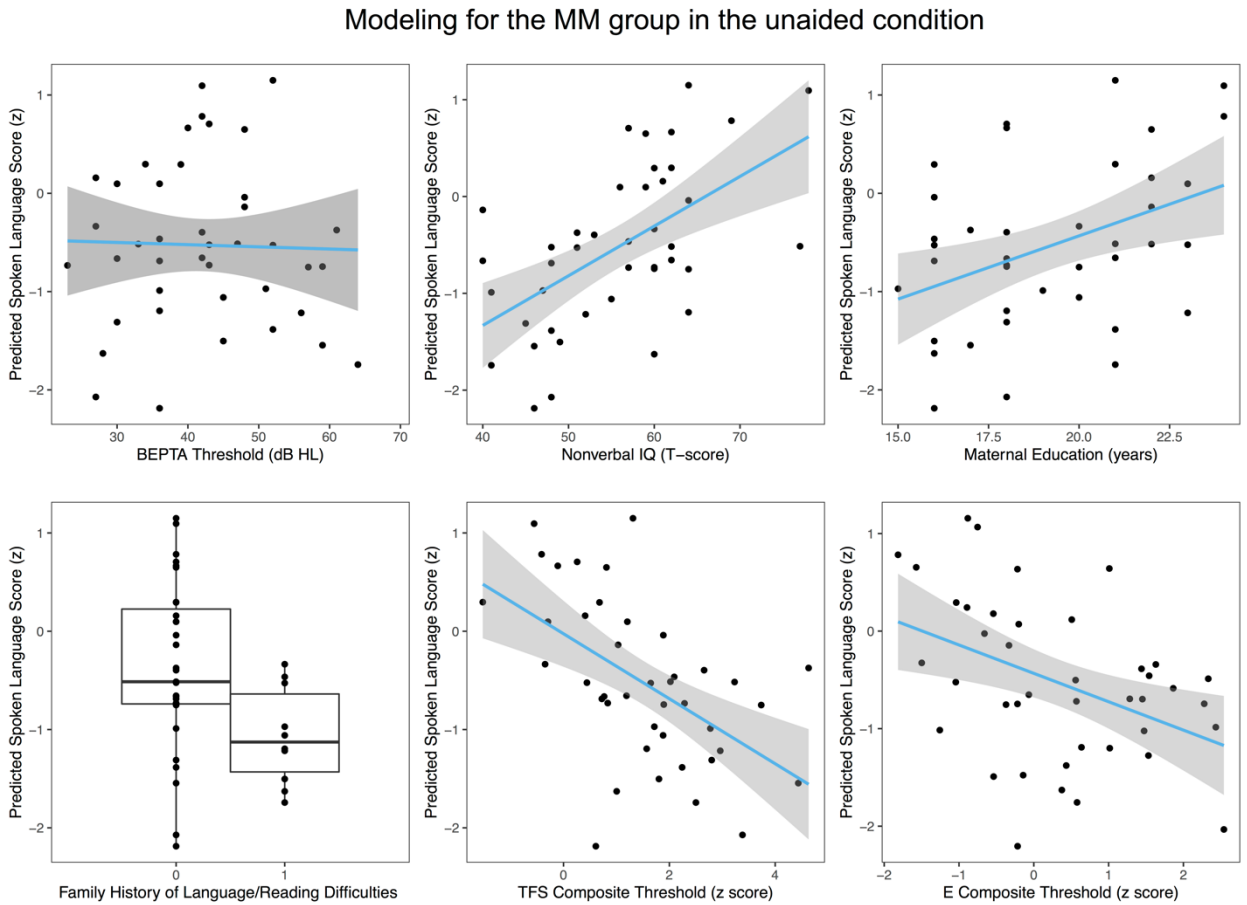

FIG 5. Relationships between the five predictor variables - BEPTA thresholds, nonverbal IQ, maternal education levels, family history of language difficulties, and unaided TFS thresholds, and predicted scores on the spoken language composite, for the best fitting model for the MM group for the unaided condition (Model 2). The relationship between unaided E thresholds and predicted spoken language scores (Model 3) is shown for comparison. Shaded areas represent the 95% confidence intervals.

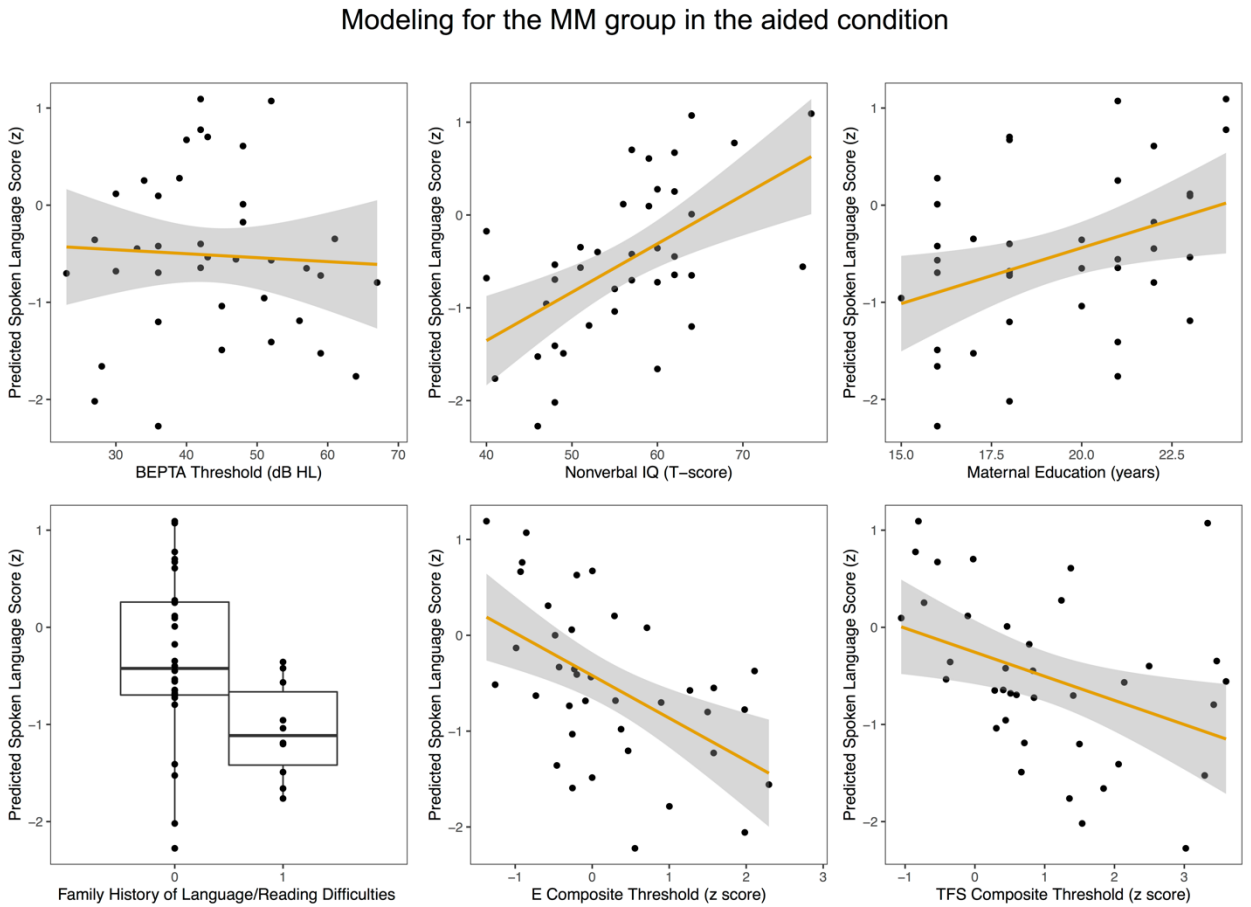

FIG 6. Relationships between the five predictor variables - BEPTA thresholds, nonverbal IQ, maternal education levels, family history of language difficulties, and aided E thresholds, and predicted scores on the spoken language composite, for the joint best fitting model for the MM aided group (Model 3). The relationship between aided TFS thresholds and predicted spoken language scores (Model 2) is also shown. Shaded areas represent the 95% confidence intervals.

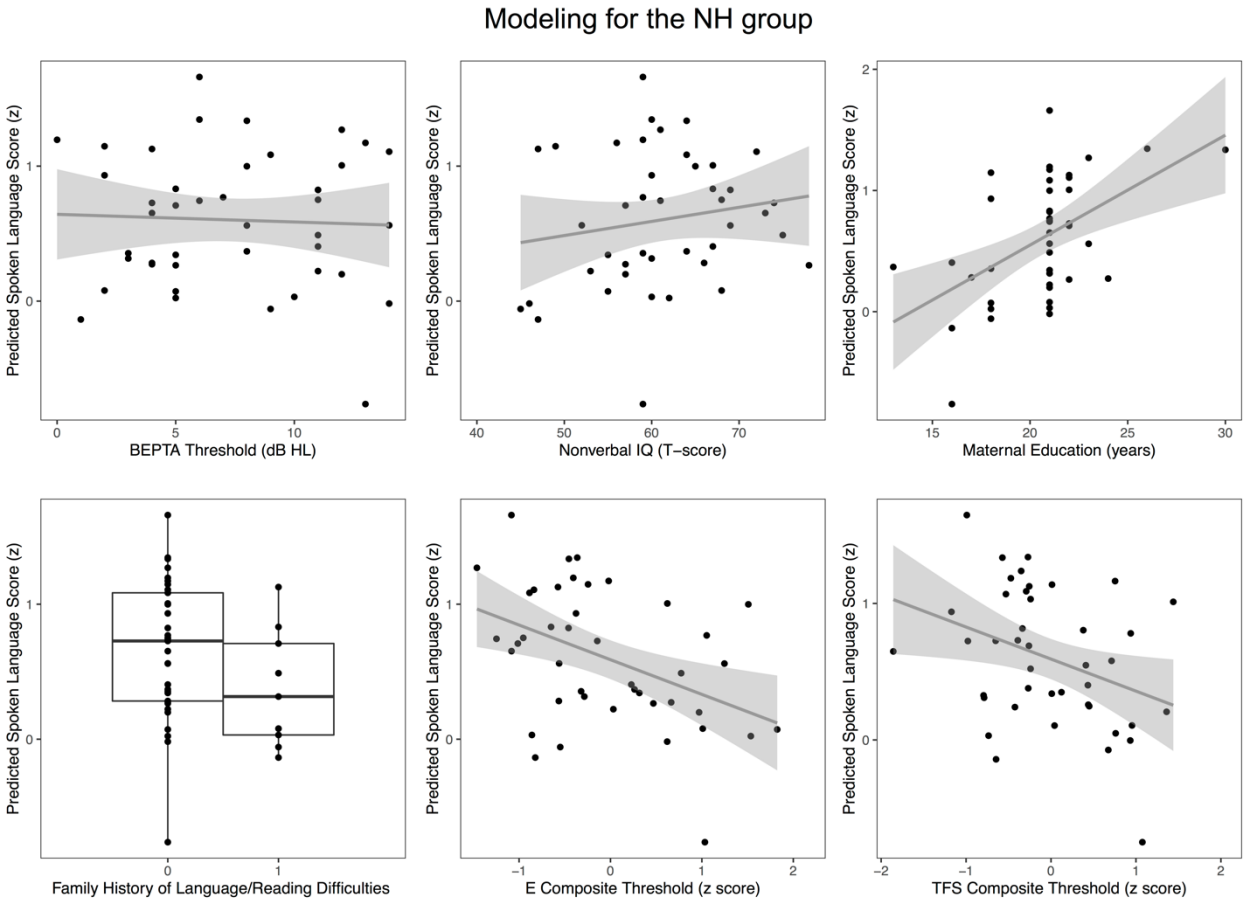

FIG 7. Relationships between the five predictor variables - BEPTA thresholds, nonverbal IQ, maternal education levels, family history of language difficulties, and E thresholds, and predicted scores on the spoken language composite, for the best fitting model for the NH group (Model 3). The relationship between TFS thresholds and predicted spoken language scores (Model 2) is shown for comparison. Shaded areas represent the 95% confidence intervals.