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Impaired frequency selectivity and sensitivity to temporal fine structure, but not envelope cues, in children with mild-to-moderate sensorineural hearing loss

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Psychophysical thresholds were measured for 8–16 year-old children with mild-to-moderate sensorineural hearing loss (MMHL; $N = 46$) on a battery of auditory processing tasks that included measures designed to be dependent upon frequency selectivity and sensitivity to temporal fine structure (TFS) or envelope cues. Children with MMHL who wore hearing aids were tested in both unaided and aided conditions, and all were compared to a group of normally hearing (NH) age-matched controls. Children with MMHL performed more poorly than NH controls on tasks considered to be dependent upon frequency selectivity, sensitivity to TFS, and speech discrimination (/bɑ/-/dɑ/), but not on tasks measuring sensitivity to envelope cues. Auditory processing deficits remained regardless of age, were observed in both unaided and aided conditions, and could not be attributed to differences in nonverbal IQ or attention between groups. However, better auditory processing in children with MMHL was predicted by better audiometric thresholds and, for aided tasks only, higher levels of maternal education. These results suggest that, as for adults with MMHL, children with MMHL may show deficits in frequency selectivity and sensitivity to TFS, but sensitivity to the envelope may remain intact.

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I. INTRODUCTION

Sensorineural hearing loss (SNHL), caused by pathology of the cochlea or auditory nerve (Moore, 2007), affects around 1.6 in every 1000 live births (Davis *et al.*, 1997) and around two in every 1000 children (Fortnum *et al.*, 2001). Aetiology is varied and includes pre-, peri-, and post-natal causes (Smith *et al.*, 2005; Walch *et al.*, 2000). However, in developed countries, around 80% of pre-lingual SNHL has a genetic basis, giving rise to both syndromic and non-syndromic conditions, in recessive and dominant forms (Shearer *et al.*, 1999). Severity is varied, and classified as either mild [better-ear pure-tone-average threshold across 0.5, 1, 2, and 4 kHz (BEPTA) of 21–40 dB hearing level (HL)], moderate (41–70 dB HL), severe (71–90 dB HL) or profound (>90 dB HL; British Society of Audiology, 2011).[1] Individuals with mild or moderate sensorineural hearing loss (MMHL) have residual hearing that is useful without hearing prostheses, although in high-income countries many are fitted with hearing aids, which go some way towards restoring audibility (Stevens *et al.*, 2013). However, in addition to causing reduced sensitivity to low-intensity sounds, SNHL also leads to changes in the way in which audible sounds are perceived [Moore, 2007; i.e., so-called auditory processing (AP)]. The goal of this study was to examine the AP abilities of 8- to 16-year-old children with MMHL.

The effects of SNHL on the adult auditory system are now relatively well understood (see Moore, 2007, for a review). SNHL is associated with reduced compression on the basilar membrane (Ruggero and Rich, 1991), leading to loudness recruitment (i.e., a more rapid than normal growth of loudness once the sound level exceeds the elevated absolute threshold) for most individuals (Moore and Glasberg, 2004). Individuals with SNHL also tend to have broader auditory filters than those with normal hearing (NH), leading to impaired frequency selectivity (i.e., the ability to resolve the spectral components of a complex sound; for review, see Moore, 2007). Moreover, evidence from animal studies suggests that SNHL may be associated with (a) reduced precision of phase locking (i.e., the synchronization of neural firings to a given auditory stimulus) to broadband stimuli in quiet and noise, and to narrowband stimuli in noise (Henry and Heinz, 2012; Woolf *et al.*, 1981; cf. Harrison and Evans, 1979; Miller *et al.*, 1997); (b) an over-representation of low-frequency and under-representation of high-frequency temporal fine structure (TFS) information (i.e., the rapid oscillations in amplitude at the output of the auditory filters, which are coded in the patterns of phase locking in the auditory

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nerve); and (c) stronger correlations in TFS information between auditory-nerve fibres with different centre frequencies (for reviews, see Henry and Heinz, 2013; Moore, 2008). However, whether or not reduced precision of phase locking in background noise happens independently of frequency selectivity is a controversial topic (e.g., Oxenham and Simonson, 2009), as is the relative importance of phase-locking information for pitch perception, particularly at high frequencies (Verschooten *et al.*, 2019). Finally, SNHL has been shown to be associated with enhanced phase locking to the envelope (i.e., relatively slow variations in the amplitude of a sound over time; Kale and Heinz, 2012).

The perceptual consequences of these changes can be measured in humans using behavioural psychophysical tasks. For adults, studies indicate that even mild or moderate levels of SNHL are associated with reduced sensitivity to a range of acoustic contrasts. For example, adults with MMHL have been shown to perform more poorly on a range of tasks thought to measure TFS processing, including frequency discrimination (FD) of low-frequency (<4–5 kHz) tones, frequency modulation detection (FMD) for low carrier frequencies (<4–5 kHz) and modulation rates ($\lesssim$10 Hz), and the discrimination of changes in the fundamental frequency ($F0$) of a complex tone (e.g., Wallaert *et al.*, 2018; for a review, see Moore, 2014). However, for many of these tasks, poor performance may be explained by poorer frequency selectivity rather than deficits in TFS (e.g. Oxenham *et al.*, 2009). In contrast, adults with MMHL have been shown to demonstrate normal or sometimes enhanced processing of envelope cues. For instance, studies have typically shown that amplitude modulation detection (AMD) is either unimpaired (Bacon and Gleitman, 1992; Bacon and Opie, 2002; Glasberg and Moore, 1989; Moore and Glasberg, 1986, 2001; Moore *et al.*, 1992; Rance *et al.*, 2004) or enhanced (Bacon and Gleitman, 1992; Lorenzi *et al.*, 2006; Moore *et al.*, 1992; Wallaert *et al.*, 2017) in adults with MMHL.

Nevertheless, the majority of research on the effects of MMHL on AP in humans has focused on older adults, leaving open the possibility that some of the deficits reported may in part have been a consequence of age-related changes unrelated to hearing function (Füllgrabe *et al.*, 2015; Hopkins and Moore, 2011; Paraouty *et al.*, 2016; Whiteford *et al.*, 2017; cf. Schoof and Rosen, 2014). Moreover, studies involving adults with predominantly acquired losses (i.e., presbycusis) are not designed to assess the developmental effects of SNHL during childhood. Recent findings from animal studies suggest that even moderate levels of *conductive* hearing loss during critical periods may have a substantial, negative impact upon auditory perceptual development (Buran *et al.*, 2014; Caras and Sanes, 2015; Rosen *et al.*, 2012; von Trapp *et al.*, 2017). We might therefore expect a greater, or altered effect of MMHL during childhood on the development of a variety of measures of AP.

To date, only a handful of studies have examined the basic AP abilities of children with MMHL (see Jerger, 2007, for a review). Rance *et al.* (2004) assessed the frequency selectivity, FD, FMD, and AMD abilities of ten 4–9 year-old children with MMHL, compared to 14 children with auditory neuropathy spectrum disorder (ANSD)[2] and ten NH age-matched controls. The MMHL group had poorer frequency selectivity than both the ANSD group and NH controls, and performed more poorly than controls on FMD for a 500-Hz, but not 4-kHz, carrier modulated at a rate of 10 Hz, suggestive of impaired TFS processing. However, they did not show poorer AMD at any of the rates tested, and their temporal modulation transfer function (AMD as a function of modulation rate) was normal. Halliday and Bishop (2005) tested the FD abilities of twenty-two 6–13 year-old children with MMHL at both 1 kHz, where phase-locking cues are available, and 6 kHz, where they are not. Children with MMHL exhibited poorer FD at both frequencies relative to NH controls. Poorer FD thresholds at 6 kHz, but not at 1 kHz, were associated with increasing severity of SNHL. Finally, Halliday and Bishop (2006) tested the FMD abilities of sixteen 8–14 year-old children with MMHL using a 1-kHz sinusoidal carrier at modulation rates of 2 Hz, where phase-locking cues are available, and 20 Hz, where they are not, both without and with added AM that was designed to force listeners to rely on phase-locking cues where possible (e.g., Moore and Skrodzka, 2002). After the removal of outliers, children with MMHL had poorer FMD thresholds on all tasks, suggestive of a general deficit in AP, rather than a specific deficit in the ability to use TFS information. Poorer FMD was generally associated with poorer hearing thresholds for the MMHL group.

The limited number of studies conducted to date leave a number of questions outstanding. First, studies have included relatively small sample sizes across relatively wide age ranges. Consequently, the effects of childhood MMHL on the development of AP have yet to be determined. Such abilities are known to develop well into late childhood and adolescence (e.g., Moore *et al.*, 2011); we might therefore expect MMHL to lead to delays or deviances in the development of these skills. Second, whereas existing studies have examined the unaided AP abilities of children with MMHL, little is known about the effects of hearing aids on AP in this group. This is an important oversight, as the majority of children with MMHL process auditory information via their hearing aids on a daily basis. Finally, whilst some AP abilities have been linked to basic sensory factors such as the severity of hearing loss (Halliday and Bishop, 2005, 2006), the effects of higher-level cognitive abilities on AP in this group have yet to be assessed. However, nonverbal IQ has been shown to be associated with AP in NH populations (e.g., Moore *et al.*, 2010). Moreover, poor performance on AP tasks can sometimes be attributable to deficits in attention rather than AP *per se*, particularly in children (Hirsh and Watson, 1996; Breier *et al.*, 2003; Roach *et al.*, 2004; Sutcliffe and Bishop, 2005; Moore *et al.*, 2008; Moore *et al.*, 2010; cf. Ferguson and Moore, 2014). Given that SNHL in adults has been linked to reduced processing efficiency (i.e., the ability to make optimal use of available sensory information; Füllgrabe *et al.*, 2015; Paraouty *et al.*, 2016; Wallaert *et al.*, 2017; 2018), we might therefore expect to see a similar, or even enhanced relationship between cognition and AP in children with MMHL.

The aims of the current study were therefore threefold. First, we aimed to examine the basic AP abilities of a relatively large ($N = 46$) group of children (aged 8- to 16-years) with MMHL, compared to a group of age-matched NH controls ($N = 44$). To do so, we measured psychophysical thresholds on a battery of AP tasks, performance on which was designed to depend upon a range of different auditory processes (i.e., sensitivity to TFS and envelope cues, and frequency selectivity), across a range of different levels of acoustic complexity (from sinusoids to complex harmonic sounds to speech sounds). We hypothesised that, regardless of age, children with MMHL would perform more poorly than their NH peers on tasks designed to be reliant upon TFS and frequency selectivity, but not on tasks designed to measure sensitivity to envelope cues alone. Second, we assessed the influence of hearing aids on AP by testing children with MMHL in both aided and unaided conditions. We hypothesised that the aided AP thresholds of children with MMHL would be lower (better) than their unaided thresholds for tasks upon which performance is known to improve with increasing level (Wier *et al.*, 1977; Zurek and Formby, 1981). However, because auditory perceptual deficits are associated with SNHL at even suprathreshold levels, we predicted that aided thresholds would remain higher (poorer) than those of NH controls for affected tasks. Finally, we examined the extent to which different AP abilities in children with MMHL were predicted by sensory (severity of SNHL), cognitive (attention and nonverbal IQ), and demographic (socio-economic status; SES) variables, by estimating these as part of a larger test battery. We predicted that AP thresholds would worsen with increasing severity of SNHL in children with MMHL, and poorer nonverbal IQ and attention in both groups.

II. METHODS

A. Participants

Participants were recruited as part of a larger study which included psychophysical, psychometric, and electrophysiological testing (see Calcus *et al.*, 2019; Halliday *et al.*, 2017a,b). The project received ethical approval from the UCL Research Ethics Committee. Informed written consent was obtained from the parents/guardians of each child and each child gave their verbal assent to participate in the study.

1. MM group

Fifty-seven 8–16 year-old children with a diagnosis of MMHL were recruited for this study. Mild hearing loss was defined as a BEPTA threshold of 21–40 dB HL (across octave frequencies 0.25–4 kHz), and moderate hearing loss was defined as a BEPTA threshold of 41–70 dB HL (British Society of Audiology, 2011). Participants were identified via Hearing Services in Local Educational Authorities across Greater London and the South East of England. Information packs were sent to parents/guardians of children who (a) had a known diagnosis of MMHL, (b) were aged 8–16 years, (c) were from monolingual English-speaking backgrounds, (d) communicated solely via the oral/aural modality (i.e., did not use sign language), and (e) did not have any other known medical, neurological or psychological conditions. Children whose hearing loss was attributed to a syndrome or neurological impairment including ANSD were excluded from the study. Therefore, the final sample comprised children who had a typical cochlear SNHL that was nonsyndromic in aetiology.

Children who met these criteria were invited to attend a first test session. During this session, pure-tone air-conduction audiometric thresholds were obtained at 0.25, 0.5, 1, 2, 4, and 8 kHz, in both ears (British Society of Audiology, 2011), using an Interacoustics AC33 audiometer with Telephonics TDH-49 headphones. In addition, nonverbal IQ was assessed using the Block Design subtest of the Wechsler Abbreviated Scale of Intelligence (WASI; Wechsler, 1999). Children were excluded from the study if they did not meet the criteria for MMHL during this session ($n = 1$), or if they did not achieve a nonverbal IQ T-score of ≥ 40 [i.e., if they scored more than one standard deviation (*SD*) below the normative mean (*M*) of 50; $n = 4$]. A further six children in this group dropped out of the study prior to completing all testing. This left 46 children (19 mild, 27 moderate SNHL; *MM group*; see Table I). Audiograms for the MM group are shown in Fig. 1. All but three of the MM group had been prescribed with bilateral hearing aids, although one participant refused to wear their aids. The age of confirmation of hearing loss ranged from 2 months to 14 years [Median (Mdn) = 57 months, M = 54 months, $SD = 36$]. The late confirmation of hearing loss for some of the children in this study is not unusual because (a) many of the children participating were born prior to the introduction of the UK national Newborn Hearing Screening Programme (NHSP), and (b) the NHSP currently only routinely screens for hearing loss >40 dB HL (i.e., children with mild levels of hearing loss are not routinely detected).

2. NH group

Forty-four NH control children (*NH group;* see Table I) aged 8–16 years were recruited via mainstream schools located in and around Greater London. Exclusion criteria were (a) known hearing loss, (b) educational difficulties, and/or (c) history of speech and/or language difficulties. The

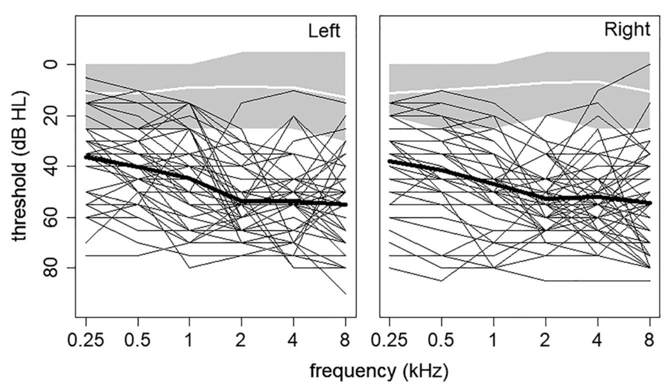

FIG. 1. Individual (thin lines) and mean (black thick lines) audiometric thresholds for the MM group, for the left and right ears. Mean thresholds for the NH group are shown as white thick lines. The shaded area indicates the range for the NH group.

TABLE I. Mean (SD) participant characteristics and between-group comparisons for the NH and MM groups. Comparisons were independent-samples *t*-tests apart from Gender which was a Fisher's exact test. All significant comparisons ($p < 0.05$) remained so after controlling for multiple comparisons (Bonferroni; $\alpha = 0.008$; boldface). Effect sizes were Cohen's *d* for *t*-tests, and odds ratio (OR) for Fisher's.

	Group		Between-group				
Variable	NH ($n = 44$)	MM ($n = 46$)	*df*	Statistic	*p*	Effect size	95% CI
Age (years)	11.5 (2.1)	11.4 (2.2)	88	0.23	0.821	0.05	[-0.8, 1.0]
Gender (M:F)	19:25	27:19			0.205	0.54	[0.2, 1.2]
M PTA threshold (dB HL)	**8.8 (4.1)**[a]	**46.0 (11.9)**	**56.3**	**−19.89**	**<0.001**	**4.16**	**[−40.9, −33.4]**
BEPTA threshold (dB HL)	**7.3 (4.0)**[a]	**43.4 (12.0)**	**55.2**	**−19.28**	**<0.001**	**4.05**	**[−39.8, −32.3]**
Maternal education (years)	20.5 (2.9)[a]	19.3 (2.6)[b]	83	1.88	0.063	0.41	[−0.1, 2.3]
Nonverbal IQ (T score)	**60.6 (8.5)**	**55.6 (8.7)**	**88**	**2.76**	**0.007**	**0.58**	**[1.4, 8.6]**

[a]$n = 43$.
[b]$n = 42$.

parents/guardians of children who qualified for inclusion were sent information packs with invitations to participate. Children whose parents/guardians expressed an interest in taking part were matched in age (to within six months) to at least one participant in the MM group. For each participant in the MM group, there was at least one NH participant who was age matched to within six months, leading to a mean age difference of <1 month between children in the MM group and their age-matched controls. All children in the NH group had PTA thresholds <20 dB HL in both ears (British Society of Audiology, 2011), with thresholds ≤25 dB HL across 0.25–8 kHz (see shaded area, Fig. 1). Likewise, all had nonverbal IQ within the normal range.

B. Procedures

Testing was carried out during two sessions at UCL, each lasting approximately 90 min, and separated by at least a week. Children were tested individually by one of two experimenters. Audiometric and psychophysical testing were completed in a double-walled sound-attenuating booth. Psychometric testing was completed in a quiet test room. Parents completed questionnaires regarding their child's current communication abilities, and their medical, social, and language developmental history. The age at which the child's mother left full-time education (maternal education) was also recorded as a proxy of SES.

1. Auditory processing test battery

a. General procedure. Children undertook a battery of seven AP tasks that required them to detect differences between sinusoids, complex harmonic sounds, and speech sounds, and which was designed to target a range of different auditory processes (see Table II). The seven tasks were: (i) FD, (ii) FMD, (iii) rise time discrimination (RT), (iv) fundamental frequency modulation detection (*F*0), (v) second formant modulation detection (F2), (vi) AMD, and (vii) speech (/bɑ/-/dɑ/) discrimination (SP). Children typically completed two threshold estimates for each of the seven AP tasks, with one estimate for each task per session. Children with MMHL who wore hearing aids completed one threshold estimate for each task when they were wearing their hearing aids (aided condition) and one when they were not (unaided condition), one per session. Tasks were completed in counterbalanced order, with the same order being used for each child for both

TABLE II. Auditory processing test battery. Tests were designed to assess AP across a range of different levels of complexity (sinusoids, complex harmonic sounds, speech) and temporal fluctuation rates (TFS, envelope; see Rosen, 1992). Auditory processes that were targeted are written in normal font, whereas processes that may have additionally contributed to performance are italicised.

Test	Standard	Target	Initial target value	Auditory process(es)
Frequency discrimination (FD)	1-kHz sinusoid	Higher-frequency sinusoid	1.5 kHz	TFS
Frequency modulation detection (FMD)	1-kHz sinusoid	1-kHz sinusoid frequency modulated at a rate of 40 Hz	40-Hz peak modulation depth (one-direction)	Envelope Frequency selectivity *Spectral sidebands*
Rise time (RT) discrimination	1-kHz sinusoid with a 15-ms rise time	1-kHz sinusoid with a longer rise time	435-ms rise time	Envelope
Fundamental frequency modulation detection (*F*0)	Complex harmonic sound	Complex harmonic sound modulated in F0 at a rate of 4 Hz, around a centre frequency of 100 Hz	16-Hz peak modulation depth (one direction)	TFS Frequency selectivity
Second formant modulation detection (*F*2)	Complex harmonic sound	Complex harmonic sound modulated in F2 at a rate of 8 Hz	200-Hz peak modulation depth (one direction)	Envelope Frequency selectivity
Amplitude modulation detection (AMD)	Complex harmonic sound	Complex harmonic sound amplitude modulated at a rate of 2 Hz	80% amplitude modulation depth	Envelope
Speech discrimination (SP)	Digitised /bɑ/ syllable	More /dɑ/-like syllable	Digitised /dɑ/ syllable	Envelope Frequency selectivity *Higher-level speech*

sessions. For children with MMHL who wore hearing aids, unaided and aided conditions were counterbalanced between participants across the two sessions. During the aided session, hearing-aid users were asked to set their hearing aids to their preferred level for everyday use.

Psychophysical testing was done via a computer-game format using in-house software. Tests used an adaptive, three-interval, three-alternative, forced-choice paradigm ("odd-one-out"). For each trial, three sounds were presented in sequence, separated by 500 ms of silence. Sounds were presented in free-field, via a single loudspeaker (Acoustics Solutions Instate 91) that was positioned facing, centred on, and approximately 1 m away from the child's head. Between the speaker and the child was a touch-screen computer monitor that was positioned below the speaker level (i.e., not obstructing the speaker). Each sound was represented on the computer screen by a cartoon character that jumped up and down in time with its respective sound. Two of the intervals contained the same (standard) sound, and the third, randomly determined interval contained a different (target) sound. Target sounds were presented with equal probability in each of the three intervals on any given trial. Participants were required to select which of the three characters "made the different sound," and responses were recorded after the offset of the third interval. Correct responses were signalled by the selected character briefly jumping up and down, and by the accumulation of a reward token at the bottom of the screen. Incorrect responses were signalled by the absence of these events. Participants were given unlimited time to respond and initiated the start of each new trial by touching a red button at the top of the screen. Each AP task utilised a different character and background scene to encourage engagement with the tests.

b. Familiarisation. Each AP task was preceded by five practice trials which contained standard-target differences that had previously been deemed suprathreshold for NH adult listeners. Participants were required to obtain $\geq$4/5 correct responses on the practice trials in order to proceed to the corresponding test. If this criterion was not met, children could repeat the practice trials up to three times. If this criterion was not reached after three sets of practice trials, the threshold estimate for the corresponding AP test was abandoned (see below). Relatively few practice trials were repeated (1.4% of trials for the NH group; 6.5% for the MM group).

c. Psychophysical procedure. A three-down one-up procedure was used to vary the difference between the standard sound and the target sound, targeting 79.4% correct on the psychometric function (Levitt, 1971). This was preceded by an initial one-down, one-up rule until the first reversal occurred (Baker and Rosen, 2001). Errors on either of the first two trials did not trigger reversals. Tracks terminated after 50 trials, or after four reversals had been achieved at the final step size (whichever came first). The step size decreased over the first three reversals and then remained constant thereafter. Thresholds were taken as the arithmetic mean of the target stimulus over the last four reversals when linear steps were used and as the geometric mean of the same when logarithmic steps were used. For NH participants and children in the MM group who did not wear hearing aids ($n = 3$), the final threshold was the arithmetic mean of the two threshold estimates, when both estimates were available. For children in the MM group who did wear hearing aids ($n = 43$), thresholds were calculated separately for each AP task from a single run for each of the unaided and aided conditions. Children were asked 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. In addition to threshold, the *SD* of the target stimuli over the final four reversals was also calculated. This measure of response variability captures the extent to which children's performance fluctuates around threshold. As such, it has been interpreted as an indicator of intrinsic attention during the tasks (Moore *et al.*, 2008).

d. Stimuli. Stimuli comprised sinusoids (FD, FMD, RT), complex harmonic sounds ($F0$, $F2$, AMD), and speech sounds (/bɑ/-/dɑ/ discrimination). For all tasks, stimuli were pre-generated to comprise a continuum from which target stimuli were selected by the adaptive tracking procedure. Sinusoids and complex-harmonic-sound stimuli were created using MATLAB (Mathworks, Natick, MA). Speech stimuli were digitised syllables that were originally recorded by a female speaker and modified in Praat (Boersma and Weenink, 2001). Sinusoids and complex-harmonic-sound stimuli were 500 ms in duration, and speech stimuli were 175 ms in duration. All stimuli were root-mean-square (rms)-normalised and were presented for all participants at a fixed level of 70 dB sound pressure level (SPL). For children in the MM group, this was equivalent to a mean sensation level (SL) of 35 dB for the sinusoidal stimuli in the unaided condition (SD = 17.6; range = 3–63 dB SL). Stimuli were ramped on and off with 15-ms linear ramps, apart from those used in the RT task, where the duration of the on-ramp of the target signal varied (see below).

e. Auditory processing tasks. Frequency discrimination (FD) of a low-frequency tone was used to assess sensitivity to TFS for sinusoidal stimuli (see Moore and Ernst, 2012). As such, FD was assessed using a fixed 1-kHz sinusoidal standard. A continuum of 27 comparison stimuli was created, by computing frequency differences from the standard in the ratio of $1/\sqrt{2}$ from 500 Hz downwards. The continuum of comparison stimuli thus had a maximum frequency of 1.5 kHz, and a minimum frequency of 1000.06 Hz (a stimulus which was never reached by any participant). The frequency difference between the standard and the target was initially 50% (i.e., 1 kHz vs 1.5 kHz). This was adaptively reduced using an initial step size that was equivalent to a factor of $\frac{1}{2}$, which then decreased over the first three reversals to $1/\sqrt{2}$, or its inverse, depending upon the direction of the change (see Moore *et al.*, 2011). Thresholds are reported as the difference (in Hz) between the standard and the target.

FMD was used to assess both sensitivity to the envelope and frequency selectivity for sinusoidal stimuli. Because FMD is thought to be based on changes in the excitation pattern (i.e., FM-induced AM) for high modulation rates (Sek and Moore, 1995), FMD was assessed using a 1-kHz sinusoid modulated at a rate of 40 Hz. However, because the ability to detect these changes would have been dependent upon the degree of auditory filtering, performance on this task is likely to have also been limited by frequency selectivity. The initial phases of both the standard (non-modulated) and target (modulated) tones were 0°. Modulated tones had peak deviations (i.e., frequency excursions from the carrier, one direction only) ranging from ±0.8 to ±40 Hz, that were spaced logarithmically across a continuum of 99 stimuli. Peak deviation varied adaptively, with an initial step size of 12 steps along the continuum, reducing to four steps over the first three reversals. Thresholds are reported as the peak deviation (in Hz) of the target tone.

RT was used to assess sensitivity to slow fluctuations in the envelope for sinusoidal stimuli. As such, stimuli for this task were 1-kHz sinusoids, with fixed fall times of 50 ms, and with rise times ranging logarithmically from 15 ms (the standard) to 435 ms across a continuum of 100 stimuli. The initial step size was 12 steps along the continuum, reducing to six over the first three reversals. Thresholds are reported as the duration of the rise time of the target stimulus (in ms).

Detection of modulation in the fundamental frequency ($F0$) of a complex harmonic sound was used to assess sensitivity to TFS for complex stimuli (see Moore and Gockel, 2011). However, performance might have also depended upon frequency selectivity, because of reduced harmonic resolvability (Bernstein and Oxenham, 2006) or because shallower slopes diminish FM-to-AM conversion (Whiteford *et al.*, 2017). $F0$ was assessed using a continuum of complex harmonic carriers created by passing a waveform containing 50 equal-amplitude harmonics (typically at a $F0$ of 100 Hz) through three single-formant resonators in cascade, each consisting of a pair of poles. Each resonator had a bandwidth of 100 Hz and they were centred at 500, 1500, and 2500 Hz, leading to an overall spectrum with three formants, characteristic of the neutral schwa vowel /ə/. The modulation rate was 4 Hz, around a centre frequency of 100 Hz, and the peak deviation ranged from 0.04 to 16 Hz, spaced logarithmically across 100 stimuli. The initial step size was 12 steps along the continuum, reducing to four over the first three reversals. Thresholds are reported as the peak deviation (one direction only, in Hz) of the $F0$ of the target stimulus.

Detection of modulation in the second formant frequency ($F2$) of a complex harmonic sound was used to assess both sensitivity to the envelope and frequency selectivity for complex stimuli. As for the FMD task, modulations in $F2$ would likely have led to FM-induced AM, but the degree of AM would have been influenced by the degree of frequency selectivity. $F2$ was assessed using a complex harmonic carrier as described for the $F0$ task (with $F0$ fixed at 100 Hz). In this task, $F1$ and $F3$ were fixed, but $F2$ was modulated at a rate of 8 Hz, with the peak deviation in frequency ranging from ±1 Hz to ±200 Hz, spaced logarithmically across 100 stimuli. The initial step size was 12 steps along the continuum, reducing to four over the first three reversals. Thresholds are reported as the peak deviation (one direction only, in Hz).

AMD of a complex harmonic sound was used to assess sensitivity to slow fluctuations in the envelope for complex stimuli. AMD was assessed using a complex harmonic carrier as described for the $F0$ task (i.e., at a fixed $F0 = 100$ Hz, and three formants). In this task, stimuli were amplitude modulated at a rate of 2 Hz, with modulation depths ranging from 0.05 to 0.8, spaced logarithmically across 100 stimuli. Note that the 500-ms stimulus duration meant that there was only a single cycle of modulation for each modulating stimulus, placed so that the minimum of the envelope was at the beginning of the sound. The initial step size was 21 steps along the continuum, reducing to seven over the first three reversals. Thresholds are expressed in dB as $20\log_{10}$ (modulation depth).

Speech discrimination (SP) was assessed using a consonant discrimination task. The two endpoints of the continuum were based on a digitized /bɑ/ (the standard) and /dɑ/ (the initial target) spoken by a female speaker, and identical to those used by Bishop *et al.* (2010). The two stimuli were adjusted to the same rms level, and the two intonation contours were made monotone at 220 Hz using Praat (Boersma and Weenink, 2001). A continuum of 100 stimuli was then constructed (including the two endpoints), using the morphing capabilities of the programme STRAIGHT (Kawahara *et al.*, 1999). STRAIGHT is a type of vocoder which performs a source/filter decomposition, extracting a variety of speech features whose values are then gradually changed through the continuum to generate a smooth trajectory of high-quality stimuli. Because the acoustic differences between the stimuli are preserved and varied slowly across the continuum, it can be difficult to say which features might be responsible for the discrimination performance. However, both on the basis of prior studies of this phonetic contrast as well as the properties of the specific stimuli here, there were two distinct cues available to listeners which would allow the discrimination. One concerns the properties of the initial release burst which was longer, more intense and with more high frequencies in its spectrum for the /dɑ/ than the /bɑ/. The other concerns the formants and their transitions, especially for $F2$, which were higher for the /dɑ/. Listeners can vary in the extent to which they weight different cues (Hazan and Rosen, 1991) but both cues here relied on sensitivity to the spectral distribution of energy, and how it evolved over time. In the adaptive procedure, the initial step size was 15 steps along the continuum, reduced to five over the first three reversals. Thresholds were measured on an arbitrary scale (in %), as the number in the continuum (from 0–99) of the target stimulus.

C. Missing data, data processing, and analyses

It was not possible to obtain a PTA threshold for one child in the NH group owing to poor compliance. Instead, a screening procedure was conducted which confirmed that this child had normal hearing (i.e., reliable detection at 20 dB HL across 0.25–8 kHz for both ears). Unaided AP thresholds were not obtained for one child in the MM group because she was unable to hear the stimuli without her hearing aids. This child had the poorest unaided PTA thresholds.

One NH child did not perform the AP assessments during the second testing session owing to time constraints. AP thresholds were not obtained for 11 tracks (two NH and nine MM, of which six were for the RT task) due to floor effects after repeated attempts (i.e., participants did not perform at or above 79% correct even at the maximal difference) and/or fewer than four reversals being achieved at the final step size. Where NH children or children with MMHL who did not wear hearing aids failed to perform two tracks for each AP task, thresholds were calculated from the first track only. Missing data were examined and it was concluded that the data were unlikely to be missing at random. Consequently, missing values were not generally replaced unless otherwise reported. To mitigate data loss, analyses included all the available data where possible, meaning that analyses for some tasks and conditions contained a slightly different subset of participants.

Thresholds for the majority of AP tasks did not meet the assumption of normality (Kolmogorov-Smirnov $p < 0.05$) as a result of positive skew (the exceptions being AMD thresholds for both groups). Where AP thresholds were non-normal, they were subject to a log-transformation (base 10), which normalised the distributions for all but two of the data sets (the exceptions being aided $F0$ and RT for the MM group). No data sets had any extreme outliers (data points $>3 \times$ interquartile range). Given that (a) the majority of AP threshold data sets met the assumption of normality after transformation, and (b) parametric statistics are relatively robust to violations of this assumption (Field, 2013), AP threshold data were analysed using parametric statistics. Response variability scores (*SD*s of target stimuli over the final four reversals) were also non-normal for a majority of tasks. No transformations successfully normalised the majority of these data and therefore nonparametric statistics were used to analyse this measure.

III. RESULTS

A. Participant characteristics

Table I shows the characteristics of the NH and MM groups. Independent-samples *t*-tests were used to assess Group differences in age, PTA thresholds, maternal education, and nonverbal IQ. Fisher's exact test was used to assess Group differences in gender. The MM group did not differ from the NH group in age, maternal education, or gender distribution, but had significantly poorer nonverbal IQ and, by design, higher (poorer) PTA thresholds. Nonverbal IQ was therefore included as a covariate in subsequent group comparisons.

B. Auditory processing thresholds

1. Unaided thresholds

Figure 2 shows the unaided thresholds for the NH and MM groups for each AP task as a function of age. To assess whether children with MMHL showed impaired performance on any of the tasks, univariate analyses of covariance (ANCOVA) were conducted on the unaided thresholds for each AP task, with Group (MM versus NH) as the between-groups factor, and Age and Nonverbal IQ as covariates (see Table III). The initial custom models included all main effects and a Group $\times$ Age interaction to ascertain differences in developmental trajectories between groups (Thomas *et al.*, 2009). If the Group $\times$ Age interaction term was not significant (which was the case for all of the tasks), it was removed from the final models, but otherwise, all main effects and covariates were retained. Cook's distance (D_i) values were calculated to establish whether any individual data points exerted undue influence on the models. No data points achieved a D_i value >1, and therefore all available data were retained.

There were significant main effects of Group on unaided thresholds for the FD, FMD, $F0$, $F2$, and SP tasks. For these tasks, unaided thresholds were significantly higher for the MM group relative to NH controls. However, the MM group did not differ significantly from the NH group on either the AMD task or the RT task after controlling for multiple comparisons (Bonferroni; $\alpha = 0.007$). There were significant main effects of Age for the FD, RT, and SP tasks, and of Nonverbal IQ for FD. Thresholds for these tasks decreased (improved) with increasing age and increasing nonverbal IQ. Finally, the Group $\times$ Age interaction for $F2$ just missed significance [$F(1, 82) = 3.92$, $p = 0.051$, $\eta p^2 = 0.05$]. To investigate this further, the effects of age on $F2$ thresholds were examined separately for the two groups, after controlling for nonverbal IQ. There was a significant, large effect of Age on $F2$ thresholds for the NH group [$F(1, 41) = 14.98$, $p < 0.001$, $\eta^2 = 0.27$], with thresholds decreasing with increasing age.

TABLE III. Between-group fixed effects of Group (MM vs. NH), Age, and Nonverbal IQ on unaided AP thresholds. Comparisons were univariate ANCOVAs controlling for Age and Nonverbal IQ. Comparisons that remained significant after controlling for multiple comparisons (Bonferroni; $\alpha = 0.007$) are shown in boldface. ηp^2 = partial η^2.

		Group			Age			Nonverbal IQ		
AP task	*df*	*F*	*p*	ηp^2	*F*	*p*	ηp^2	*F*	*p*	ηp^2
FD	1, 85	**30.36**	**<0.001**	**0.26**	**17.58**	**<0.001**	**0.17**	**14.51**	**0.001**	**0.15**
FMD	1, 84	**30.11**	**<0.001**	**0.26**	0.27	0.608	0.00	0.00	0.989	0.00
RT	1, 79	5.82	0.018	0.07	**10.59**	**0.002**	**0.12**	6.22	0.015	0.07
*F*0	1, 85	**15.89**	**<0.001**	**0.16**	1.69	0.197	0.02	1.60	0.209	0.02
*F*2	1, 82	**57.14**	**<0.001**	**0.58**	2.14	0.148	0.03	3.48	0.066	0.04
AMD	1, 85	1.95	0.166	0.02	1.18	0.280	0.01	1.44	0.234	0.02
SP	1, 85	**11.39**	**0.001**	**0.12**	**9.50**	**0.003**	**0.10**	5.80	0.018	0.06

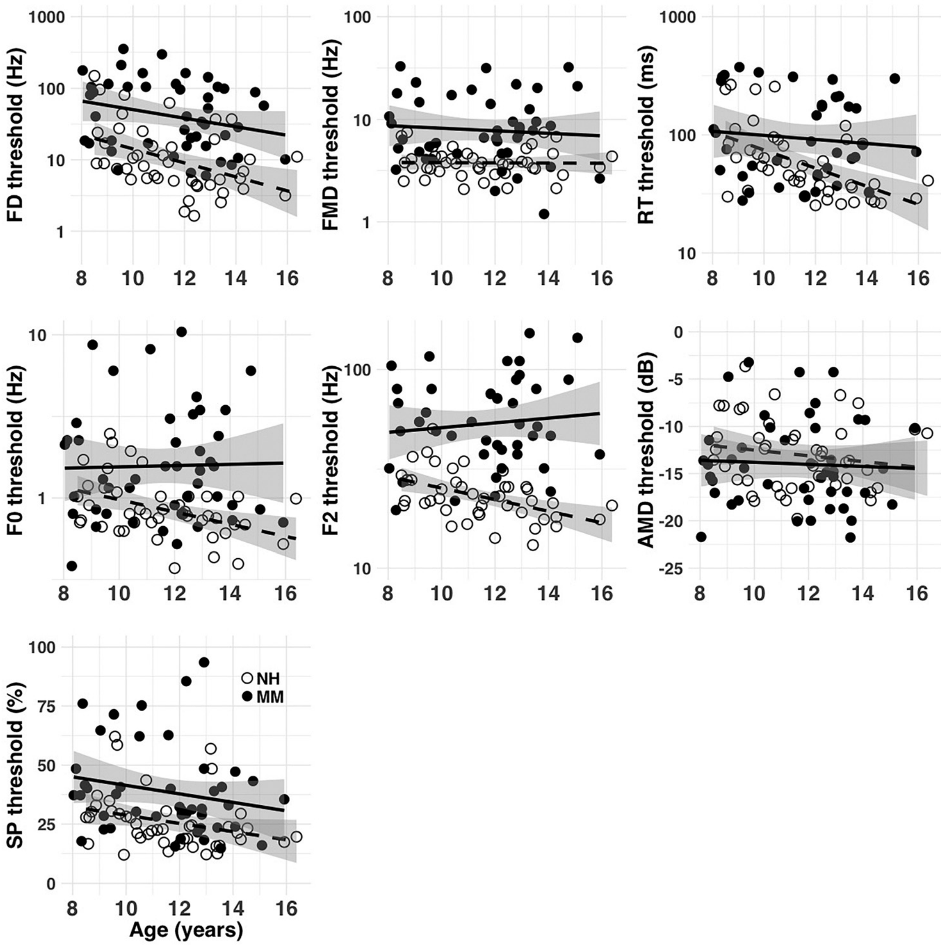

FIG. 2. Individual unaided thresholds for the MM group (filled circles) and NH group (open circles) for the seven AP tasks as a function of age. Regression slopes for age are shown for the MM group (unbroken line) and NH group (broken line). The shaded area indicates the ±95% CI of each regression slope.

In contrast, for the MM group, the effect of Age on $F2$ thresholds was not significant [$F(1, 40) = 0.00$, $p = 0.955$, $\eta^2 = 0.00$]. As is clear from Fig. 2, this interaction does not complicate the interpretation of the main effect of Group in that the MM group performed more poorly than controls at every age.

2. Aided thresholds

Figure 3 shows the unaided versus aided AP thresholds for the MM hearing-aid users. Note that for ease of comparison across tasks, age-standardised thresholds are plotted in Fig. 3, whereas the analyses were conducted on non-age-standardised thresholds. However, the results were the same whether age-standardised or non-age standardised thresholds were used. To assess whether thresholds were lower in the aided condition than in the unaided condition, a series of repeated-measures ANOVAs was conducted on the AP thresholds of MM hearing-aid users with Condition (unaided versus aided) as the repeated measure. There were significant main effects of Condition on thresholds for the FMD and $F2$ tasks [$F(1, 39) = 20.29$, $p < 0.001$, $\eta p^2 = 0.34$] and [$F(1, 38) = 23.60$, $p < 0.001$, $\eta p^2 = 0.38$], respectively. Thresholds on the FD and RT tasks did not differ significantly between aided and unaided conditions after controlling for multiple comparisons (Bonferroni; $\alpha = 0.007$) [$F(1, 40) = 7.36$, $p = 0.010$, $\eta p^2 = 0.16$] and [$F(1, 34) = 4.41$, $p = 0.043$, $\eta p^2 = 0.12$], respectively. Aided thresholds did not differ from unaided thresholds for the $F0$, AMD, and SP tasks [$F(1, 40) = 3.63$, $p = 0.064$, $\eta p^2 = 0.08$], [$F(1, 40) = 3.27$, $p = 0.078$, $\eta p^2 = 0.08$], and [$F(1, 39) = 0.56$, $p = 0.459$, $\eta p^2 = 0.01$], respectively.

Figure 4 shows the aided AP thresholds for MM hearing-aid users compared to the unaided thresholds for NH controls for each AP task as a function of age. To assess whether aided thresholds for the MM hearing-aid users were comparable to thresholds for the NH group, a series of univariate ANCOVAs was conducted (see Table IV). Group was the between-subjects factor, and Age and Nonverbal IQ were covariates. A Group × Age interaction term was entered into the initial models but was removed where not significant (which was the case for all models). There were significant main effects of Group for the FD, $F0$, $F2$, and SP tasks, driven by the higher aided thresholds of the MM group. The aided FMD, RT, and AMD thresholds for the MM group did not differ significantly from the unaided thresholds for the NH group. However, it is worth noting that unaided thresholds for the MM group for two of those tasks (RT and AMD) already did not differ from those of controls. There were significant effects of Age on thresholds for the RT, $F0$, AMD, and SP tasks, and of Age and Nonverbal IQ for FD, with thresholds decreasing with both increasing age and increasing nonverbal IQ. Finally, there was again a Group × Age interaction on thresholds for the $F2$ task that was not significant after controlling for multiple comparisons (Bonferroni; $\alpha = 0.007$) [$F(1, 81) = 4.77$, $p = 0.032$, $\eta p^2 = 0.06$]. *Post hoc* analyses showed that aided

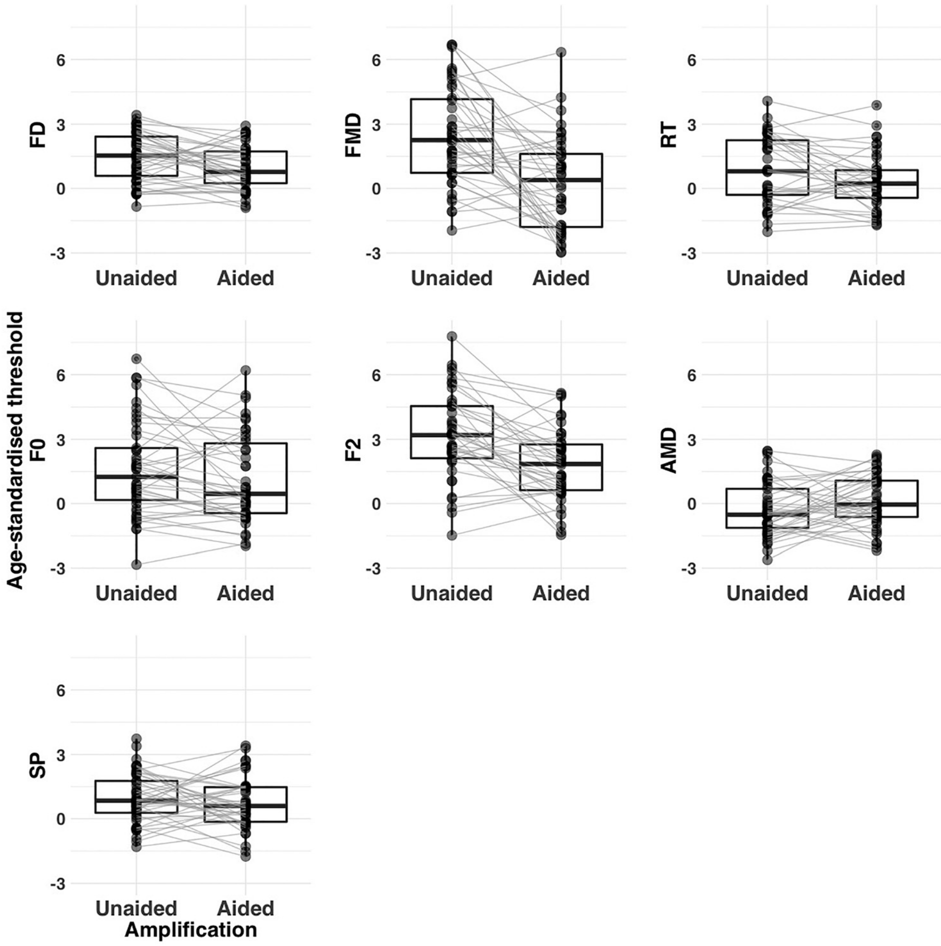

FIG. 3. Individual (circles), median (horizontal line), ± interquartile range (box), unaided versus aided age-standardised thresholds for MM hearing-aid users for the seven AP tasks.

*F*2 thresholds also did not improve with age for the MM group [$F(1, 39) = 0.10$, $p = 0.752$, $\eta^2 = 0.00$], leading to a relative worsening of thresholds with age for the MM group compared to their NH peers (see Fig. 4).

3. Response variability

It is possible that the poorer AP thresholds of the MM group were due to them exhibiting poorer attention during psychophysical testing relative to NH controls. Response variability scores (*SDs*) for the MM and NH groups did not change with age for any task (Spearman's Rho, all $ps > 0.05$). Therefore, response variability for the two groups was compared for each task and condition using Mann-Whitney U-tests (see Supplementary Table I).[3] After controlling for multiple comparisons (Bonferroni; $\alpha = 0.007$), there were no significant differences between groups for any of the tasks, for either the unaided or aided conditions.

C. Components of AP

To verify our interpretation of the processes underlying performance on the different tasks, AP thresholds for the MM group only were entered into a principal components analysis (PCA). To do so, AP thresholds for the MM group for each task and condition were first subject to a regression against age, partialling out age based on the data from the NH group. The resultant residuals were standardised, resulting in a set of age-standardised thresholds (equivalent to *z*-scores; $M = 0$; $SD = 1$). The majority of these thresholds met the assumption of normality (Kolmogorov-Smirnov $p \geq 0.05$; the exception was aided *F*0). Because of the large number of missing data (only 28 participants had data for all 14 variables), missing values were replaced with the mean age-standardised threshold for each AP task.

A PCA followed by Varimax rotation was then conducted on age-standardised AP thresholds. The initial R-matrix containing all seven AP tests in unaided and aided conditions identified three tasks (AMD unaided, SP unaided, and FMD aided) for which fewer than 50% of correlations with other tasks were ≥ 0.3 (see Supplementary Table II).[3] These tasks were therefore excluded from the analysis and the PCA was re-run (Field, 2013). The final model had a sample size of 46, with a participant-to-variable ratio of 4.1. Given the small sample size and high number of variables, the following analyses should therefore be considered as exploratory. However, the Kaiser-Meyer-Olkin estimate was 0.70, suggesting that sampling was adequate (Hutcheson and Sofroniou, 1999). Extracted communalities were high ($M > 0.6$) indicating that the AP thresholds shared a substantial amount of variance. Three factors had an eigenvalue >1, and examination of the scree plot supported the decision to retain these factors. The rotated component matrix is shown in Table V. To assist with interpretation, factor loadings that were more extreme than ± 0.4 are shown in bold.

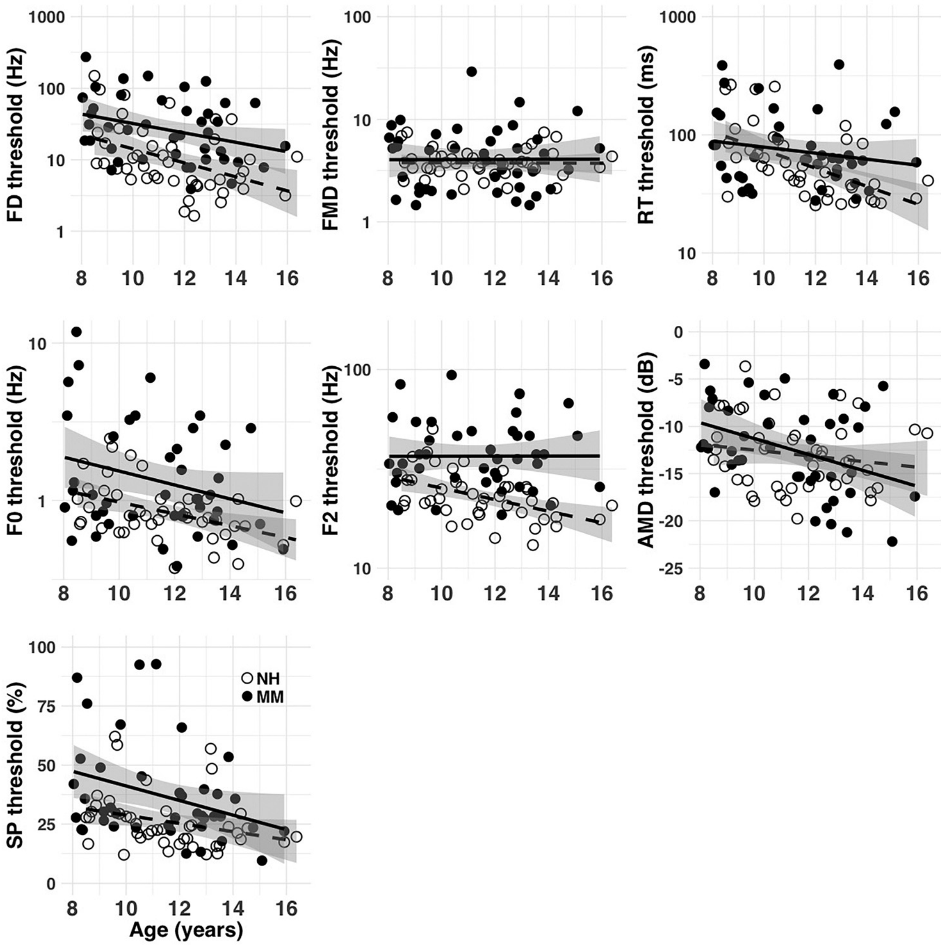

FIG. 4. Individual aided thresholds for the MM group (filled circles) for the seven AP tasks as a function of age. The individual unaided thresholds of the NH group (open circles) are shown for comparison as per Fig. 2. Regression slopes for age are shown for the MM group (unbroken line) and NH group (broken line). The shaded area indicates the ±95% CI of each regression slope.

The first component accounted for 35% of the variance and showed high loadings on a subset of tasks thought to reflect both TFS ($F0$ unaided and aided) and envelope cues (RT unaided and aided, AMD aided). It was therefore named the *TFS-E* component. The second component accounted for an additional 18% of the variance, and had high loadings mostly on tasks thought to reflect frequency selectivity (i.e., $F2$ unaided and aided, FMD unaided), as well as a high negative loading on aided SP. This component was therefore named Frequency Selectivity (*FS*). Finally, the third component accounted for an additional 10% of the variance and showed high loadings on predominantly aided tasks (FD, $F2$, and SP), albeit with a moderate loading on unaided FD. Nonetheless, because of the predominance of aided tasks contributing to this component, it was therefore named Aided AP.

D. Predictors of AP

Correlations between thresholds on the AP tasks and the sensory (i.e., severity of SNHL), cognitive (attention, nonverbal IQ), and demographic (age, SES) measures for the MM group are also shown in Supplementary Table II.[3] To investigate the extent to which these measures predicted AP for children with MMHL, backward stepwise linear regressions were conducted for each of the three AP components

TABLE IV. Between-group fixed effects of Group (MM vs. NH), Age, and Nonverbal IQ on unaided AP thresholds for the NH group and aided AP thresholds for the MM group. Comparisons that remained significant after controlling for multiple comparisons (Bonferroni; $\alpha = 0.007$) are shown in boldface. $\eta p^2 =$ partial η^2.

		Group			Age			Nonverbal IQ		
AP task	*df*	*F*	*p*	ηp^2	*F*	*p*	ηp^2	*F*	*p*	ηp^2
FD	1, 82	**12.52**	**0.001**	**0.13**	**20.06**	**<0.001**	**0.20**	**12.46**	**0.001**	**0.13**
FMD	1, 82	0.01	0.931	0.00	0.09	0.765	0.00	3.73	0.057	0.04
RT	1, 81	1.16	0.285	0.01	**14.70**	**<0.001**	**0.15**	3.76	0.056	0.04
$F0$	1, 82	**8.73**	**0.004**	**0.10**	**9.18**	**0.003**	**0.10**	0.33	0.566	0.00
$F2$	1, 82	**35.74**	**<0.001**	**0.30**	4.37	0.040	0.05	0.19	0.665	0.00
AMD	1, 82	0.12	0.734	0.00	**7.73**	**0.007**	**0.09**	0.25	0.621	0.00
SP	1, 81	**7.85**	**0.006**	**0.09**	**11.90**	**0.001**	**0.13**	0.14	0.713	0.00

TABLE V. Rotated component matrix (Varimax) for the seven AP tasks and two conditions for the MM group, minus the AMD and SP unaided and FMD aided tasks (see text). Component loadings $>\pm 0.4$ are shown in bold, and loadings $<\pm 0.1$ are not shown. TFS: Temporal fine structure; E: Envelope; FS: Frequency selectivity.

Task	(1) TFS-E	(2) FS	(3) Aided AP
*F*0 unaided	**0.788**	0.196	
*F*0 aided	**0.760**		0.290
RT unaided	**0.655**	**0.548**	−0.187
RT aided	**0.611**	0.194	
AMD aided	**0.608**		0.299
*F*2 unaided		**0.794**	
SP aided	0.396	**−0.651**	**0.456**
FMD unaided	0.284	**0.629**	0.112
*F*2 aided		**0.587**	**0.553**
FD unaided	0.369	**0.514**	**0.415**
FD aided	0.175		**0.837**

identified from the PCA. AP components rather than thresholds were used to reduce the number of variables tested and minimise the risk of multicollinearity between variables owing to high correlations between the different tasks. For each component, BEPTA thresholds, age, nonverbal IQ, maternal education levels, and mean response variability over the unaided and aided conditions were entered into the initial models. Missing data were replaced with the mean. Variables that did not significantly improve the fit of each model were iteratively removed until the final (optimal) models were produced.

Table VI shows the final models for the three AP components for the MM group. Correlation matrices between the three components and the entered variables are shown in Supplementary Table III.[3] For the TFS-E component, the final model was (just) significant [$F(1, 44) = 4.09$, $p = 0.049$], with a single predictor variable, BEPTA thresholds, contributing significantly to the model. However, the final model only accounted for 9% of the variance. For the FS component, both age and BEPTA contributed significantly to the final model, which was significant [$F(2, 43) = 10.96$, $p < 0.001$], and accounted for 34% of the variance. Finally, for the Aided AP component, the final model retained both BEPTA thresholds and maternal education as the two significant predictors, explaining 21% of the variance [$F(2, 43) = 5.80$, $p = 0.006$].

TABLE VI. Linear models of predictors for each of the three AP components for the MM group. Predictors that made a significant contribution to each model ($p < 0.05$) are shown in bold.

Component	Predictors	*B*	*SE B*	*β*	*p*	95% CI *b*
(1) TFS-E						
	Constant	−1.05	0.54		0.057	[−2.14, 0.03]
	BEPTA	**0.0**	**0.01**	**0.29**	**0.049**	**[0.00, 0.05]**
(2) FS						
	Constant	−3.79	0.84		<0.001	[−5.49, −2.09]
	BEPTA	**0.04**	**0.01**	**0.46**	**0.001**	**[0.02, 0.06]**
	Age	**0.19**	**0.06**	**0.40**	**0.002**	**[0.07, 0.30]**
(3) Aided AP						
	Constant	1.27	1.13		0.268	[−1.01, 3.54]
	BEPTA	**0.03**	**0.01**	**0.35**	**0.015**	**[0.06, 0.05]**
	Maternal education	**−0.13**	**0.05**	**−0.33**	**0.020**	**[−0.24, −0.02]**

IV. DISCUSSION

The basic auditory perceptual abilities of children with MMHL were assessed with three main goals. First, we aimed to determine which auditory processes were affected amongst children with MMHL, and whether development of AP was delayed or deviant in this group. Second, we asked whether amplification, provided through the wearing of hearing aids, would improve the AP abilities of children with MMHL, and/or bring their performance to within normal limits. Third, we investigated the components and predictors of AP for children with MMHL. Regardless of age, 8- to 16-year-old children with MMHL obtained poorer AP thresholds relative to their NH peers, apart from for two measures (AMD and RT). Hearing aids improved performance on only a subset of tasks. Group differences could not be attributed to differences in nonverbal IQ, and children with MMHL did not show greater response variability than NH controls. Rather, AP performance of children with MMHL could be described in terms of three underlying components, which appeared to reflect TFS and envelope processing (TFS-E), frequency selectivity (FS), and Aided AP. Performance on all three components deteriorated with increasing severity of hearing loss. In addition, the age-normalized thresholds of the MM group worsened with increasing age for the FS component, and with decreasing levels of maternal education for Aided AP.

A. Deficits in temporal fine structure and frequency selectivity but not envelope cues

Our findings may be partially explained in terms of impairments in TFS processing in children with MMHL. TFS carries information about both the frequency of sinusoidal stimuli and the *F*0 of complex stimuli, for carriers $<\sim$4–5 kHz (Moore, 2008; Moore and Ernst, 2012). Consequently, the impaired performance of the MM group on both the FD and *F*0 tasks in this study suggests that children with MMHL may show reduced sensitivity to, or utility of, TFS cues (for reviews, see Henry and Heinz, 2013; Moore, 2008). There are several explanations as to why this might be the case, including (a) reduced precision of phase locking in individual auditory neurons (Woolf *et al.*, 1981), (b) reductions in auditory neural populations (Kujawa and Liberman, 2009), (c) disruptions to the peripheral (Ruggero, 1994) and central (Shamma, 1985; Carney *et al.*, 2002) coding of TFS based on reduced correlation of outputs at adjacent points along the basilar membrane, (d) increases in the complexity and/or variability of neural TFS owing to broader auditory filters (Moore, 2008), (e) mismatches between neural TFS and the responses at characteristic-frequency locations on the basilar membrane (Henry *et al.*, 2016), and/or (f) central changes including increases in internal noise (Wallaert *et al.*, 2017; 2018) and/or decreases in neural inhibition (Takesian *et al.*, 2012; Mowery *et al.*, 2015), following SNHL (for review, see Moore, 2014).

Nevertheless, contra Woolf *et al.* (1981), animal models have shown that cochlear hearing loss has relatively little impact upon the phase-locking of peripheral auditory neurons to the TFS of narrowband stimuli in quiet (for review, see Henry and Heinz, 2013). Our findings of impaired FD in quiet in children with MMHL therefore suggest that these deficits may arise beyond the level of phase-locking of individual neurons. Note that, because levels were not roved, it is possible that participants at least partially based their judgments on frequency-specific changes in loudness, so that the true deficit may have been greater than we measured.

Our findings are also consistent with an interpretation of poorer frequency selectivity in children with MMHL. The FMD task we used was unusual, in that the modulation rate of 40 Hz was too fast for TFS to have been useful (Moore and Sek, 1995, 1996; Sek and Moore, 1995), so the frequency modulation (FM) is likely to have been converted to amplitude modulation (AM) in the cochlea (Glasberg and Moore, 1986; Zwicker, 1952). However, the depth of these modulations would have depended crucially on the bandwidth and slope of the auditory filters, with narrower filters and steeper slopes leading to deeper FM-induced AM. It is also possible that spectral sidebands were detectable for this task, particularly in the aided condition (Ernst and Moore, 2010; Moore and Sek, 1996). For the *F*2 task, AMD is also likely to have been critical, given that the *F*2 variation would likely have resulted in AM at the outputs of the auditory filters tuned just below and above *F*2 (Lyzenga and Carlyon, 1999). However, again, performance would have also been dependent upon frequency selectivity, in that distinct frequency channels would have needed to receive these modulations in order for them to be detected. It is therefore possible that the poorer performance of the MM group on both the *F*2 and FMD tasks resulted from them having broader cochlear filters, thereby leading to reduced FM-to-AM conversion at the output of those filters (see also Paraouty *et al.*, 2016).

Nonetheless, our results suggest that where envelope cues were able to reach the central auditory systems of children with MMHL, they were relatively well preserved. The AMD and RT tasks involved slow ($\leq$2 Hz) changes in amplitude over time over the entire bandwidth of the stimuli; discrimination of stimuli based on these changes therefore likely required the detection and utilisation of envelope cues. The relatively unimpaired performance of children with MMHL on these tasks therefore suggests that, consistent with adult (Grose *et al.*, 2016; Sek *et al.*, 2015; Schlittenlacher and Moore, 2016) and animal studies of SNHL (Henry and Heinz, 2013), children with MMHL may exhibit sensitivity to the auditory envelope that is at least comparable to that of their NH peers (see also Rance *et al.*, 2004). It remains possible that children with MMHL would have exhibited even better thresholds on these tasks had they been tested at comparable SLs to the NH group (Bacon and Gleitman, 1992; Moore *et al.*, 1992; Moore *et al.*, 1996; Füllgrabe *et al.*, 2003; Wallaert *et al.*, 2017), although we did not observe this in the aided condition, where differences in SL between groups were reduced. Nonetheless, whether our results can be explained by enhanced neural phase-locking to envelope cues (Kale and Heinz, 2010, 2012) or reduced compression on the basilar membrane (Moore *et al.*, 1996; Moore *et al.*, 1992; Wallaert *et al.*, 2017) remains to be seen.

B. Deviance rather than delays in development

Although impaired, the AP abilities of children with MMHL tended to develop at a similar rate to those with NH. Therefore, our data may be interpreted as being consistent with a pattern of *delayed* AP development in children with MMHL (Thomas *et al.*, 2009), to the extent that we might expect them to "catch up" during adolescence or adulthood. However, three findings lead us to be cautious about this interpretation. First, thresholds improved with age for the NH group for only a subset of tasks. Therefore, AP thresholds for children with NH may have already reached adult levels for some tasks (notably, FMD and AMD; see Dawes and Bishop, 2008; Hartley and Moore, 2002; Moore *et al.*, 2011; Thompson *et al.*, 1999; Werner, 1998; cf. Hall and Grose, 1994). Second, age-normalized thresholds for the MM group on the FS component deteriorated with age, and there was a trend for an interaction with age on *F*2 in both the unaided and aided conditions. These findings were driven by an improvement in thresholds with age for the NH group, but not for the MM group. This pattern of performance is suggestive of an *absence* of development with age in children with MMHL and is consistent with the notion that hearing loss may place an "upper limit" on the development of auditory perception (e.g., Caras and Sanes, 2015). Third, as reviewed above, adults with MMHL have also been found to show impairments on similar tasks. Therefore, we would expect that children who develop SNHL in early life would show deficits in AP that either remain or are exacerbated as they grow older. It remains to be seen whether SNHL that occurs during a sensitive or critical period in children has a disproportionate effect on the development of AP in humans (see Mowery *et al.*, 2015, for findings in gerbils).

C. Beneficial effects of (good) hearing aids on AP

Amplification in the form of hearing aids did not consistently improve the AP abilities of children with MMHL, either at the group level or at the level of the individual. For tasks where aided thresholds were improved relative to unaided ones (i.e., FMD, *F*2 and, marginally, FD and RT), this may have been due to the increased SLs of the aided stimuli. FD at 1 kHz has been shown to improve with increasing level (Wier *et al.*, 1977), as has FMD, albeit only up to 25 dB SL and for slow modulation rates (Zurek and Formby, 1981). Stimuli for some of the MM group likely fell within that range in the unaided condition. In addition, for the FMD task, hearing aids may have increased the audibility of spectral sidebands. Multi-channel compression, as is commonly used in hearing aids, would have resulted in spectral sidebands being amplified more than the carrier frequency, making it less likely that the sidebands would be masked by the carrier, and thus giving rise to additional cues for discrimination in the aided condition. This may account for the fact that aided FMD thresholds for the MM group were as good as those for NH controls, even though unaided thresholds were not.

Nonetheless, hearing aids might have been expected to be associated with more widespread improvements in AP than we saw, and there are several explanations as to why this was not the case. One possibility is that some of the hearing aids used in the current study were not set to optimal levels. The output of a given hearing aid will depend upon many factors, including the stimulus, the type of hearing aid (e.g., the amount and speed of compression, frequency range, use or not of frequency lowering), and the prescription formula used and/or achieved (e.g., Hedrick and Rice, 2000; Jenstad and Souza, 2005; Stelmachowicz *et al.*, 1995; for a review, see Souza, 2002). We did not consistently record the type(s) of hearing aids used in the current study, and equipment failure meant that it was not possible to measure their fit. However, better thresholds on the Aided AP component were predicted by higher levels of maternal education, a marker for SES. It is not inconceivable to imagine that children with higher levels of SES may have had better hearing aids, better fittings, and/or greater frequency of appointments to keep fittings up-to-date, as well as more consistent use of their aids as a result of parental monitoring. A recent large-scale study showed that greater degrees of aided audibility were associated with faster rates of language growth between 2 and 6 years in children with mild-to-severe SNHL (Tomblin *et al.*, 2015). Moreover, better language outcomes have been reported for in those children with SNHL who show more consistent use of hearing aids (Walker *et al.*, 2015). It is possible that these findings are mediated by improvements to AP for those children who have access to better-fitting hearing aids that are used more consistently. Nonetheless, it is also clear that this is unlikely to be the whole story and, whereas hearing aids can go some way towards compensating for a loss of sensitivity to sounds, they are currently unable to redress other, suprathreshold effects of SNHL.

D. Contributions of sensory but not non-sensory factors

Finally, our results may shed light on relative contributions for sensory versus nonsensory factors on the AP of children with SNHL. Regarding sensory factors, our results indicate an important role for severity of hearing loss on AP in this group. Severity of hearing loss predicted performance on all three of the AP components identified from the PCA, with worsening audiometric thresholds being associated with poorer AP performance for the MM group. For the FS component, this effect was marked, with audiometric thresholds making a large, significant contribution to the final model which, in turn, accounted for 34% of the variance of this component. For the TFS-E component, in contrast, the effect was less striking; While audiometric thresholds made a significant and exclusive contribution to the model, the final model accounted for only 9% of the variance of this component. This may seem counter-intuitive, given that sensitivity to TFS might be expected to worsen with increasing SNHL. However, the fact that the TFS and envelope tasks all showed positive rather than opposing loadings on this component suggests that the TFS-E component may in fact have reflected the integrity (or otherwise) of inner hair cells as opposed to the outer hair cell damage that is dominant in typical cochlear SNHL. Indeed, children with ANSD have been shown to perform poorly on tasks sensitive to both TFS and envelope cues, but have intact frequency selectivity (Rance *et al.*, 2004). In contrast, performance on the FS component may be more reflective of the outer hair cell damage that is more characteristic of SNHL.

Regarding nonsensory factors, contrary to our predictions we did not find evidence that these contributed to the poorer AP performance of children with MMHL. Indeed, although children with MMHL on average had slightly lower nonverbal IQ than their NH peers, group differences in AP were nonetheless observed after controlling for nonverbal IQ, and nonverbal IQ, at least as measured in this study, was not associated with or predictive of performance on any of the AP components identified. Moreover, response variability in this study did not differ between groups or predict performance on any of the AP components for the MM group. This contrasts with the literature on NH children, where nonsensory factors including attention and nonverbal IQ have been shown to exert a role on AP (e.g., Moore *et al.*, 2010). However, it may be that by placing an upper limit on performance, SNHL reduces the contributions of non-sensory factors on AP in children. Further research is needed to test this hypothesis.

E. Conclusions

Children with MMHL were found to show deficits on a range of behavioural AP tasks, in particular those requiring frequency selectivity and sensitivity to TFS. In contrast, tasks which required sensitivity to slow envelope cues alone were not problematic for this group. AP deficits were manifested at suprathreshold levels (i.e., levels above the detection threshold), and were not fully remediated by the use of hearing aids. Moreover, AP abilities were differentially associated with severity of hearing loss and maternal education, but not nonverbal IQ or attention. Given that deficits in TFS processing (Lorenzi *et al.*, 2006; Moore 2008; cf. Swaminathan and Heinz, 2012) and frequency selectivity (Davies-Venn *et al.*, 2015) have been linked to speech-in-noise (SiN) difficulties in adults with SNHL, future studies examining the relationship between AP, SiN, and language in children with MMHL are warranted.

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[1]Note that the American Speech and Hearing Association (ASHA) uses a different classification system for degrees of hearing loss, namely, slight (16–25 dB HL), mild (26–40 dB HL), moderate (41–55 dB HL), moderately severe (56–70 dB HL), severe (71–90 dB HL), and profound (91+ dB HL) (Clark, 1981). MMHL as defined here is approximately equivalent to the slight to moderate-severe categories defined by ASHA.

[2]ANSD is thought to result from damage to the inner hair cells, the auditory nerve, or the juncture between the two, and is diagnosed when an individual has otoacoustic emissions and/or cochlear microphonics present, but an absent or abnormal auditory brainstem response (e.g., Starr *et al.*, 2000).

[3]See supplementary material at https://doi.org/10.1121/1.5134059 for Supplementary Tables I–III.

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