Impaired sensitivity to temporal fine structure but not the envelope for children with mild-to-moderate sensorineural hearing loss

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ABSTRACT

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 predominantly reliant 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 (/ba/-/da/), 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 for 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 their frequency selectivity and sensitivity to TFS, but that sensitivity to envelope cues may remain intact.

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 2 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 HL), moderate (41-70 dB HL), severe (71-90 dB HL) or profound (>90 dB HL; British Society of Audiology, 2011)ⁱ. Individuals with mild or moderate SNHL (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; c.f., 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 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, this is a controversial topic (see Oxenham and Simonson, 2009; Swaminathan and Heinz, 2012). 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 for 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 ($< 4\text{-}5$ kHz) tones, frequency modulation detection (FMD) for low carrier frequencies ($< 4\text{-}5$ kHz) and modulation rates ($\sim < 10$ 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, 2014b). 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) for 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; c.f. 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)ⁱⁱ 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 22, 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 16, 8-14 year-old children with MMHL 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. Poorer FMD was generally associated with worse hearing thresholds for the MMHL group.

However, 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 for 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 for 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, there is evidence to suggest that attention can modulate performance on behavioural AP tasks, particularly for 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; c.f. 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; Wallaert *et al.*, 2018), we might therefore expect to see a similar, or even enhanced relationship between cognition and AP for children with MMHL.

The aims of the current study were therefore three-fold. 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 designed to assess sensitivity to a range of acoustic features. These included measures considered to be predominantly reliant upon the utilisation of TFS cues (FD, and detection of modulations in F_0), sensitivity to the envelope (rise-time discrimination (RT) and AMD), frequency selectivity (FMD at a fast (40 Hz) modulation rate, and detection of modulations in the second formant (F_2)), and speech discrimination (SP; /ba/-/da/). 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 the envelope. 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 on tasks upon which performance is known to improve with increasing level (i.e., FD and possibly FMD; Wier *et al.*, 1977; Zurek & 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 for children with MMHL, and poorer nonverbal IQ and attention for both groups.

II. METHODS

A. Participants

Participants were recruited as part of a larger study which included psychophysical, psychometric, and electrophysiological testing (see Calcutt *et al.*, 2017; Halliday, *et al.*, 2017a, 2017b). 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 20-40 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 of 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 8-15 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 language problems. The 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 6 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 6 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 every threshold ≤ 25 dB HL across 0.25-8 kHz. Likewise, all had nonverbal IQ within the normal range.

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.

B. Procedures

Testing was carried out during two sessions at UCL, each lasting approximately 90 minutes, 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 or discriminate differences between simple nonspeech sounds, complex nonspeech sounds, and speech sounds across a range of different timescales (s, ms, μ s). The seven tasks were: (i) frequency discrimination (FD; simple nonspeech, μ s), (ii) frequency modulation detection (FMD; simple nonspeech, ms), (iii) rise time discrimination (RT; simple nonspeech, s), detection of modulations in the (iv) fundamental frequency (F0, complex nonspeech, μ s), (v) second formant (F2, complex nonspeech, ms), and (vi) amplitude (AMD, complex nonspeech, s) of a complex harmonic sound characteristic of the neutral schwa vowel /ə/, and (vii) /ba/-/da/ discrimination (speech). 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 whilst they were wearing their hearing aids (aided condition) and one when they were not (unaided condition). Tasks were completed in counterbalanced order, with the same order being used for each child for both 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 4 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 selected 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 simple nonspeech (FD, FMD, RT), complex nonspeech (F0, F2, AMD), and speech sounds (/ba/ /da/ discrimination). For all tasks, stimuli were pre-generated to comprise a series of continua from which stimuli were selected by the adaptive tracking procedure. Simple and complex nonspeech stimuli were created using Matlab at a sampling rate of 44.1 kHz. Speech stimuli were digitised syllables (sampling rate 30 kHz). Nonspeech stimuli were 500 ms in duration, and speech stimuli were 175 ms in duration. Stimuli were presented for all participants at a fixed sound pressure level of 70 dB SPL. For children in the MM group, this was equivalent to a mean sensation level of 35 dB SL for the simple

nonspeech 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 test, where the duration of the on ramp of the target signal varied (see below).

e. Auditory processing tasks

Frequency discrimination (FD) was assessed using a fixed (i.e. non-roving) 1-kHz sinusoidal standard. A continuum of 28 stimuli was created, ranging from 1.5 kHz to 1 kHz (the standard), with frequency differences spaced in the ratio of $1/\sqrt{2}$ from 1.5 kHz. 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 2 which then decreased over the first three reversals to 1.412 (see Moore *et al.*, 2011). Thresholds are reported as the difference (in Hz) between the standard and the target.

Frequency modulation detection (FMD) was assessed using a 1-kHz sinusoid modulated at a rate of 40 Hz. The initial phases of both the standard (non-modulated) and target (modulated) tones were 0° . Modulated tones had a modulation indices (MI; modulation depth/rate) ranging from 0.02 to 1 in steps of 0.01 across a continuum of 99 stimuli. MI varied adaptively, with an initial step size of 0.12, reducing to 0.04 over the first three reversals. Thresholds are reported as the peak deviation (one direction only, in Hz) of the target tone.

Rise time discrimination (RT) was assessed with a 1-kHz sinusoid. Stimuli for this test had fixed fall times of 50 ms, with rise time ranging logarithmically from 15 ms (the standard) to 435 ms across a continuum of 100 stimuli. The initial step size was 12, reducing to 6 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 fundamental frequency (F_0) 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 simple resonators. 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 MI ranged from 0.01 to 4, spaced logarithmically across 100 stimuli. The initial step size was 12, reducing to 4 over the first three reversals. Thresholds are reported as the peak deviation (one direction only; in Hz) of the F0.

Detection of modulation in second formant frequency (F2) was assessed using a complex harmonic carrier as described for the F0 task. In this task, F2 was modulated at a rate of 8 Hz, with the deviation in frequency ranging from ± 1 Hz to ± 200 Hz, spaced logarithmically across 100 stimuli. The initial step size was 12, reducing to 4 over the first three reversals. Thresholds are reported as the peak deviation (one direction only; in Hz).

Amplitude modulation detection (AMD) was assessed using a complex harmonic carrier as described for the F0 task. In this task, stimuli were amplitude modulated at a rate of 2 Hz, with the MI ranging from 0.05 to 0.8, spaced logarithmically across 100 stimuli. The initial step size was 21, reducing to 7 over the first three reversals. Thresholds are expressed in dB as $20\log_{10}(\text{MI})$.

Speech discrimination (SP) was assessed using a consonant discrimination task. The two endpoints of the continuum were digitised /ba/ (the standard) and /da/ syllables, identical to those used by Uwer, *et al.*, 2002, and were originally spoken by a German female speaker. A continuum of 98 in-between stimuli was constructed using the morphing capabilities of the programme STRAIGHT (Kawahara *et al.*, 1999). The initial step size was 15 places along the continuum, which reduced to five places 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, where possible analyses included all the available data, 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 $p < .05$) 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 (*SDs* of selected 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 for 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 (see Table I). Nonverbal IQ was therefore included as a covariate in subsequent group comparisons.

B. Auditory processing thresholds

1. Unaided thresholds

Fig. 2 shows the unaided thresholds for the NH and MM groups for each AP task as a function of age. 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 II). 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, it was removed from the final model for each task. 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 (poorer) 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; $\alpha = .007$). There were significant main effects of Age on the FD, RT, and SP tasks, and of Nonverbal IQ on 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 [$F(1, 82) = 3.92, p = .051, \eta p^2 = .05$]. 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 [$F(1, 41) = 14.98, p < .001, \eta^2 = .27$], with thresholds decreasing (improving) with increasing age. In contrast, for the MM group, the effect of Age on F2 thresholds was not significant [$F(1, 40) = 0.00, p = .955, \eta^2 = .00$]. 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

Fig. 3 shows the unaided versus aided AP thresholds for the MM hearing-aid users. With the exception of AMD, thresholds for all tasks were generally lower (better) in the aided condition than the unaided condition. To assess the statistical significance of these effects, 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 [$F(1, 39) = 20.29, p < .001, \eta p^2 = .34$] and [$F(1, 38) = 23.60, p < .001, \eta p^2 = .38$], respectively.

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 $\pm$ 95% CI of each regression slope.

Thresholds on the FD and RT tasks did not differ significantly between aided and unaided conditions after controlling for multiple comparisons (Bonferroni; $\alpha = .007$) [$F(1, 40) = 7.36$, $p = .010$, $\eta p^2 = .16$] and [$F(1, 34) = 4.41$, $p = .043$, $\eta p^2 = .12$], respectively. Aided thresholds did not differ from unaided thresholds for the F0, AMD, and SP tasks [$F(1, 40) = 3.63$, $p = .064$, $\eta p^2 = .08$], [$F(1, 40) = 3.27$, $p = .078$, $\eta p^2 = .08$], and [$F(1, 39) = 0.56$, $p = .459$, $\eta p^2 = .01$], respectively.

Fig. 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. A series of univariate ANCOVAs was conducted on the aided thresholds for MM hearing-aid users and the unaided thresholds for NH controls (see Table III). Group was the between-subjects factor, Age and Nonverbal IQ were covariates, and a Group $\times$ Age interaction was included where significant. There were significant main effects of Group for the FD, F0, F2, and SP tasks, driven by the higher (poorer) aided thresholds of the MM group relative to the unaided thresholds for NH controls. 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 on FD, with thresholds decreasing (improving) with both increasing age and increasing nonverbal IQ. Finally, there was again a Group $\times$ Age interaction on thresholds for the F2 task that was not significant after controlling for multiple comparisons (Bonferroni; $\alpha = .007$) [$F(1, 81) = 4.77$, $p = .032$, $\eta p^2 = .06$]. Once again, F2 thresholds did not improve with age for the MM group [$F(1, 39) = 0.10$, $p = .752$, $\eta^2 = .00$], leading to a relative worsening of thresholds with age for the MM group compared to their NH peers (see Fig. 4).

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

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 $\pm 95\%$ CI of each regression slope.

3. Response variability

It is possible that the poorer AP thresholds of the MM group were due to their 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 $ps > .05$). Therefore, response variability for the two groups was compared for each task and condition using Mann-Whitney U-tests (see Supplementary Table I)ⁱⁱⁱ. After controlling for multiple comparisons (Bonferroni; $\alpha = .007$), 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 pattern of performance on the different tasks, AP thresholds for the MM group were entered into a principal components analysis (PCA). 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 $p \geq .05$; the exception was aided F0). 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 principal component analysis (PCA) followed by Varimax rotation was 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) which failed to correlate with other tasks. 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 .70, suggesting that sampling adequacy was acceptable (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 IV. To assist with interpretation, factor loadings that were more extreme than ± 0.4 are shown in bold.

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 on tasks thought to reflect frequency selectivity (i.e., F2 unaided and aided, FMD unaided) and TFS (FD unaided), as well as a high negative loading on aided SP. This component was therefore named *FS-TFS*. 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

Finally, to examine the predictors of AP in children with MMHL, a backward stepwise linear regression was conducted for each of the three AP components identified from the PCA. AP components rather than AP 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 again 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 V 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 IIⁱⁱⁱ. For the TFS-E component, the final model was (just) significant [$F(1, 44) = 4.09, p = .049$], and contained the predictor variable BEPTA thresholds only which contributed significantly to the model. However, the final model only accounted for 9% of the variance. For the FS-TFS component, both age and BEPTA contributed significantly to the final model, which was significant [$F(2, 43) = 10.96, p < .001$], and accounted for 34% of the variance. Finally, for the Aided AP component, the final model retained both BEPTA thresholds and maternal education the two significant predictors, explaining 21% of the variance [$F(2, 43) = 5.80, p = .006$].

IV. DISCUSSION

The basic auditory perceptual abilities of children with MMHL were assessed with three main goals. First, we aimed to determine which AP abilities 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 did not lead to significant widespread improvements in AP. 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 and TFS (FS-TFS), and Aided AP. Performance on all three components deteriorated with increasing severity of hearing loss, whereas FS-TFS additionally worsened with age, and Aided AP with decreasing maternal education.

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

Our findings may be explained by impairments in TFS processing for children with MMHL. TFS carries information about both the frequency of pure-tone stimuli and the F0 of complex stimuli, for carriers $< \sim 4\text{-}5$ kHz (Moore, 2008; Moore and Ernst, 2012). Consequently, the impaired performance of the MM group on both the FD and F0 tasks in this study suggests that children with MMHL, like adults, 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, Wallaert *et al.*, 2018) and/or decreases in *neural inhibition* (Takesian *et al.*, 2012; Mowery *et al.*, 2015), following SNHL (for review, see Moore, 2014). Nevertheless, 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 for children with MMHL therefore suggest that these deficits may arise beyond the level of phase-locking of individual neurons.

Our findings are also consistent with an interpretation of poorer frequency selectivity for 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, so the FM was probably detected via a place of excitation mechanism. However, it is possible that spectral sidebands were detectable, particularly in the aided condition (Ernst and Moore, 2010; Moore and Sek, 1996). For F2, we had anticipated that AMD skills might be critical, given that the F2 variation would likely result in amplitude modulation at the outputs of the auditory filters tuned just below and above F2 (Lyzenga and Carlyon, 1999). However, F2 and AMD thresholds did not load on the same component, whereas FMD and F2 did. Moreover, F2 was also the task upon which the MM group showed particularly impaired performance (unlike AMD and RT). It is therefore likely that the performance of the MM group on both the F2 and FMD tasks was limited by reduced frequency selectivity, which would have led to reduced FM-to-AM conversion in the cochlea (Glasberg and Moore, 1986).

Nonetheless, the ability of children with MMHL to use envelope cues was seemingly relatively well preserved. The AMD and RT tasks involved slow changes in amplitude over time; 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, like adults (Grose *et al.*, 2016; Sek *et al.*, 2015; Schlittenlacher and Moore, 2016) and animals (Henry and Heinz, 2013) with SNHL, 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 may have exhibited even better thresholds on these tasks had they been tested at comparable sensation levels (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 for 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; c.f. Hall and Grose, 1994). Second, age-normalized thresholds for the MM group on the FS-TFS component deteriorated with age. Moreover, there was a trend for an interaction with age on F2 in both unaided and aided conditions, driven by the fact that whereas F2 thresholds for the NH group improved with age, those for the MM group did not. This pattern of performance is suggestive of an *absence* of development with age for children with MMHL, and is consistent with the notion that hearing loss during 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, F2 and, marginally, FD and RT), this may have been due to the increased sensation levels (SL) 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 for the MM group was as good as the NH controls, even though unaided performance was inferior.

Nonetheless, hearing aids might have been expected to be linked to 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 aid will depend upon many factors, including the stimulus, the type of 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. 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 for children with mild-to-severe SNHL (Tomblin *et al.*, 2015). Moreover, better language outcomes have been reported for those children with SNHL who show more consistent use of hearing aids (Walker *et al.*, 2015). It may therefore be the case 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 the relative contributions of 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-TFS 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 reflect the integrity (or otherwise) of inner hair cells as opposed to 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-TFS 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 non-sensory 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, but not envelope cues. These 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 have been proposed to underlie the speech-in-noise (SiN) difficulties of adults with SNHL (Lorenzi *et al.*, 2006; Moore 2008), future studies examining the relationship between AP, SiN, and language for children with MMHL are therefore warranted.

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L.F.H. conceived of, designed and coordinated the study, analysed the data, and drafted the manuscript. S.R. prepared a subset of the stimuli, and helped draft the manuscript. O.T. collected and analysed the data, and helped draft the manuscript. A.C. prepared the figures and commented on the manuscript. All authors gave final approval for publication.

ENDNOTES

ⁱNote 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.

ⁱⁱReflective of damage to the inner hair cells, the auditory nerve, or the juncture between the two, and diagnosed when an individual has present otoacoustic emissions and/or a cochlear microphonic but an absent or abnormal auditory brainstem response (e.g. Starr et al., 2000).

ⁱⁱⁱSee supplementary material at [URL will be inserted by AIP] for Supplementary Tables I and II.

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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 ($p < .05$) remained so after controlling for multiple comparisons (Bonferroni; $\alpha = .008$; boldface). Effect sizes were Cohen's *d* for *t*-tests, and odds ratio (OR) for Fisher's. ^a*n* = 43; ^b*n* = 42.

Variable	Group		<i>df</i>	Statistic	Between-group		
	NH (n = 44)	MM (n = 46)			<i>p</i>	Effect size	95% CI
Age (years)	11.5 (2.1)	11.4 (2.2)	88	0.23	.821	0.05	[-0.8, 1.0]
Gender (M:F)	19:25	27:19			.205	0.54	[0.2, 1.2]
PTA mean (dB)	8.8 (4.1)^a	46.0 (11.9)	56.3	-19.89	<.001	4.16	[-40.9, -33.4]
BEPTA (dB)	7.3 (4.0)^a	43.4 (12.0)	55.2	-19.28	<.001	4.05	[-39.8, -32.3]
Maternal education (years)	20.5 (2.9) ^a	19.3 (2.6) ^b	83	1.88	.063	0.41	[-0.1, 2.3]
Nonverbal IQ (T score)	60.6 (8.5)	55.6 (8.7)	88	2.76	.007	0.58	[1.4, 8.6]

Table II: 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; $\alpha = .007$) are shown in boldface. ηp^2 = partial η^2 .

AP task	<i>df</i>	Group			Age			Nonverbal IQ		
		<i>F</i>	<i>p</i>	ηp^2	<i>F</i>	<i>p</i>	ηp^2	<i>F</i>	<i>p</i>	ηp^2
FD	1, 85	30.36	<.001	.26	17.58	<.001	.17	14.51	.001	.15
FMD	1, 84	30.11	<.001	.26	0.27	.608	.00	0.00	.989	.00
RT	1, 79	5.82	.018	.07	10.59	.002	.12	6.22	.015	.07
F0	1, 85	15.89	<.001	.16	1.69	.197	.02	1.60	.209	.02
F2	1, 82	57.14	<.001	.58	2.14	.148	.03	3.48	.066	.041
AMD	1, 85	1.95	.166	.02	1.18	.280	.01	1.44	.234	.02
SP	1, 85	11.39	.001	.12	9.50	.003	.10	5.80	.018	.06

Table III: 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; $\alpha = .007$) are shown in boldface. ηp^2 = partial η^2 .

AP task	<i>df</i>	Group			Age			Nonverbal IQ		
		<i>F</i>	<i>p</i>	ηp^2	<i>F</i>	<i>p</i>	ηp^2	<i>F</i>	<i>P</i>	ηp^2
FD	1, 82	12.52	.001	.132	20.06	<.001	.197	12.46	.001	.132
FMD	1, 82	0.01	.931	.00	0.09	.765	.00	3.73	.057	.04
RT	1, 81	1.16	.285	.01	14.70	<.001	.15	3.76	.056	.04
F0	1, 82	8.73	.004	.10	9.18	.003	.10	0.33	.566	.00
F2	1, 82	35.74	<.001	.30	4.37	.040	.05	0.19	.665	.00
AMD	1, 82	0.12	.734	.00	7.73	.007	.09	0.25	.621	.00
SP	1, 81	7.85	.006	.09	11.90	.001	.13	0.14	.713	.00

Table IV: 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. TFS: Temporal fine structure; E: Envelope; FS: Frequency selectivity.

Task	Component		
	(1) TFS-E	(2) FS-TFS	(3) Aided AP
F0 unaided	.788	.196	
F0 aided	.760		.290
RT unaided	.655	.548	-.187
RT aided	.611	.194	
AMD aided	.608		.299
F2 unaided		.794	
SP aided	.396	-.651	.456
FMD unaided	.284	.629	.112
F2 aided		.587	.553
FD unaided	.369	.514	.415
FD aided	.175		.837

Table V: Linear models of predictors for each of the three AP components for the MM group. Predictors that made a significant contribution to each model ($p < .05$) are shown in bold.

Component	Predictors	<i>B</i>	<i>SE B</i>	β	<i>p</i>	95% CI <i>b</i>
(1) TFS-E	Constant	-1.05	0.54		.057	[-2.14, 0.03]
	BEPTA	0.0	0.01	.29	.049	[0.00, 0.05]
(2) FS-TFS	Constant	-3.79	0.84		<.001	[-5.49, -2.09]
	BEPTA	0.04	0.01	.46	.001	[0.02, 0.06]
	Age	0.19	0.06	.40	.002	[0.07, 0.30]
(3) Aided AP	Constant	1.27	1.13		.268	[-1.01, 3.54]
	BEPTA	0.03	0.01	.35	.015	[0.06, 0.05]
	Maternal education	-0.13	0.05	-.33	.020	[-0.24, -0.02]