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Impact of Personal Frequency Modulation Systems on Behavioral and Cortical Auditory Evoked Potential Measures of Auditory Processing and Classroom Listening in School-Aged Children with Auditory Processing Disorder

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Abstract

Background: Personal frequency modulation (FM) systems are often recommended for children diagnosed with auditory processing disorder (APD) to improve their listening environment in the classroom. Further evidence is required to support the continuation of this recommendation.

Purpose: To determine whether personal FM systems enhance auditory processing abilities and classroom listening in school-aged children with APD.

Research Design: Two baseline assessments separated by eight weeks were undertaken before a 20-week trial of bilateral personal FM in the classroom. The third assessment was completed immediately after the FM trial. A range of behavioral measures and speech-evoked cortical auditory evoked potentials (CAEPs) in quiet and in noise were used to assess auditory processing and FM outcomes. Perceived listening ability was assessed using the Listening Inventory for Education–United Kingdom version (LIFE-UK) questionnaire student and teacher versions, and a modified version of the LIFE-UK questionnaire for parents.

Study Sample: Twenty-eight children aged 7–12 years were included in this intervention study. Of the 28 children, there were 22 males and six females.

Data Collection and Analysis: APD Tests scores and CAEP peak latencies and amplitudes were analyzed using repeated measures analysis of variance to determine whether results changed over the two baseline assessments and after the FM trial. The LIFE-UK was administered immediately before and after the FM trial. Student responses were analyzed using paired *t*-tests. Results are described for the (different) pre- and post-trial teacher versions of the LIFE-UK.

Results: Speech in spatial noise (SSN) scores improved by 13% on average when participants wore the FM system in the laboratory. Noise resulted in increased P1 and N2 latencies and reduced N2 amplitudes. The impact of noise on CAEP latencies and amplitudes was significantly reduced when participants wore the FM. Participants' LIFE-UK responses indicated significant improvements in their perceived listening after the FM trial. Most teachers (74%) reported the trial as successful, based on LIFE-UK ratings. Teachers' and parents' questionnaire ratings indicated good agreement regarding the outcomes of the FM trial. There was no change in compressed and reverberated words, masking level difference, and sustained attention scores across visits. Gaps in noise, dichotic digits test, and SSN (hard words) showed practice effects. Frequency pattern test and SSN easy word scores did

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not change between baseline visits, and improved significantly after the FM trial. CAEP N2 latencies and amplitudes changed significantly across visits; changes occurred across the baseline and the FM trial period.

Conclusions: Personal FM systems produce immediate speech perception benefits and enhancement of speech-evoked cortical responses in noise in the laboratory. The 20-week FM trial produced significant improvements in behavioral measures of auditory processing and participants' perceptions of their listening skills. Teacher and parent questionnaires also indicated positive outcomes.

Key Words: auditory plasticity, auditory processing disorder, classroom listening, cortical auditory evoked potential, FM, intervention

Abbreviations: ADHD = attention deficit/hyperactivity disorder; ANOVA = analysis of variance; APD = auditory processing disorder; ASHA = American Speech-Language-Hearing Association; CAEP = cortical auditory evoked potentials; CELF-4 = Clinical Evaluation of Language Fundamentals-Fourth Edition; CRW = compressed and reverberated words; DDT = dichotic digits test; EEG = electroencephalogram; FM = frequency modulation; FPT = frequency pattern test; GIN = gaps in noise; ISI = interstimulus interval; IVA-CPT = integrated visual and auditory-continuous performance test; LIFE-UK = Listening Inventory For Education–United Kingdom version; MLD = masking level difference; SD = standard deviation; SNR = signal-to-noise ratio; SPL = sound pressure level; SSN = speech in spatial noise

INTRODUCTION

The use of FM (frequency modulation) amplification systems to enhance the auditory environment, in combination with other language-based or metacognitive strategies, has been recommended for the comprehensive management of auditory processing disorder (APD) (Chermak and Musiek, 1992); however, few studies have investigated the benefits of these management approaches for APD (Keith and Purdy, 2014). FM amplification systems are used to improve the classroom signal-to-noise ratio (SNR). FM systems are wireless devices that receive distant auditory input via a radio signal, amplify and then transmit the signal to the ear of a listener (Stein, 1998).

The benefits of personal FM and sound-field technologies for the general school population and individuals at risk for listening and learning (e.g., due to hearing impairment) are well documented (Hawkins, 1984; Arnold and Canning, 1999; Mendel et al, 2003; Anderson and Goldstein, 2004; Iglehart, 2004; Heeney, 2006; Massie and Dillon, 2006a,b). Very little data have been published; however, documenting the efficacy of personal FM as a management strategy for students with APD (Stach et al, 1987; Rosenberg et al, 1999; ASHA, 2005).

The strongest indicators for the use of personal FM as a management strategy are thought to be deficits on monaural, low-redundancy speech (e.g., time-compressed speech tests) and dichotic speech tests (e.g., staggered spondaic word test, dichotic digits test [DDT]) (Rosenberg, 2002; Bellis, 2003). Stein (1998) recommended that FM systems are suitable for children with problems in binaural separation, binaural integration, auditory closure, and listening in the presence of competing background noise. Rosenberg (2002) and Bellis (2003) recommended FM units for certain APD subtypes only that exhibit a primary problem on speech-in-noise tasks. Based on this premise, Rosenberg (2002) suggested a few contraindications to fitting FM. For instance, according to Rosenberg (2002), children with "prosodic deficits," "integration deficits," or "auditory association deficits" should not be fitted with FM, since their model of APD specifies that the primary problem in these children is not a speech-in-noise deficit. These models are largely theoretical and lack empirical support.

Hence, it is unclear whether there are subtypes of APD that will not benefit from FM use, or whether all children with APD would benefit from FM devices. APD is often comorbid with other conditions such as reading and language disorder (Sharma et al, 2009) and attention deficit/hyperactivity disorder (ADHD) (Ptok et al, 2006), and hence very large-scale studies are needed to determine the impact of comorbid conditions and specific auditory processing deficits on FM benefit. The current study is a preliminary investigation of the benefits of enhanced SNR from personal FM use for a group of children diagnosed with APD, without considering the specific profile of difficulties or comorbid conditions of the individual children.

Personal FM Systems and Children with APD

There are few published studies on the uses and benefits of personal FM systems for children with APD. Friederichs and Friederichs (2005) reported the benefits of a personal system for nine males and one female (ages 7–14, mean = 10 years) with ADHD and suspected APD. Participants were required to use the personal FM system in the morning for at least five hours a day and trialed the system for 12 months with assessments at six-month intervals (beginning, six months, and the end). Friederichs and Friederichs (2005) found a significant improvement in the performance of the ADHD group compared with an age-matched control group on a frequency discrimination task after six months and one year of FM system use. In addition, they reported that a questionnaire revealed positive changes in social behaviors, attentiveness, and the hearing profile of the children with ADHD. Cortical auditory evoked potentials (CAEPs) were recorded and an increase in P2 amplitude after the FM system trial was reported. These results suggest that personal FM systems provide benefit to children with ADHD and suspected APD based on a range of subjective and objective outcome measures; however, the sample size was relatively small and participants in Friederichs and Friederichs' (2005) study did not have confirmed APD.

A recent study assessed the benefits of personal FM systems in children diagnosed with APD (Johnston et al, 2009). These researchers evaluated the speech perception and psychosocial status of ten children (eight male, two female; mean age 11 years 8 months) diagnosed with APD both before and after a personal FM system trial. The postassessment was conducted at least five months following the initial fitting of the bilateral personal FM system. Results of this study revealed improved academic and speech perception outcomes, and improved psychosocial status (Johnston et al, 2009).

Impact of Auditory Training on CAEPs

A novel aspect of the Friederichs and Friederichs' (2005) study was the use of CAEPs as an outcome measure. CAEPs are obligatory cortical responses that can be recorded using a range of stimuli including tones and speech, while the participant listens passively, doing a task such as reading or watching a video (Cone-Wesson and Wunderlich, 2003). The effects of short-term auditory training on CAEPs have been demonstrated in adult listeners with normal auditory function (Tremblay et al, 2001). CAEPs are also enhanced (i.e., morphology improves, amplitude increases, and/or latency decreases) by longer-term auditory experience in adults with hearing loss who have received a hearing aid (Gatehouse, 1992; Munro, 2008) or cochlear implant (Purdy et al, 2001).

In children, the morphology of cortical responses are somewhat different from those in adults, because of their slow maturational time course (Ponton et al, 2000). Children who are profoundly deaf who receive a cochlear implant show changes in CAEP amplitudes and latencies with auditory experience (Beynon et al, 2002; Sharma et al, 2002; Gordon et al, 2005). CAEP abnormalities have been reported in children with APD (Purdy et al, 2002; Bishop and McArthur, 2004); but to our knowledge, the paper by Friederichs and Friederichs (2005) is the first to utilize CAEPs as an objective tool for determining the impact of enhancing the auditory environment (via a personal FM system) on auditory function. Whereas Friederichs and Friederichs used tonal stimuli, a number of studies have investigated CAEPs to speech stimuli in children with learning problems and auditory processing difficulties (Cunningham et al, 2001; Warrier et al, 2004; Wible et al, 2005). Warrier et al (2004) found that CAEP waveforms were more degraded by noise in children with learning problems than in the control group, primarily because of the effects of noise on the latency of the N2 peak. Since speech perception in noise is a primary area of difficulty for children with APD (Bamiou et al, 2001; Chermak et al, 2002), the impact of the FM system on speech-evoked CAEPs in noise was explored in the current study.

Although the use of personal FM is widely recommended for children with APD, there is limited evidence for the benefits of FM with this population and there is no consensus regarding the best ways to measure the outcomes of FM use. It is anticipated that personal FM would have a direct benefit of enhancing speech perception in noise; but the effect of long periods of FM use on a range of auditory processing abilities is not established. Thus, a number of outcome measures were explored, including speech perception and speech-evoked CAEPs in quiet and in noise, and measures of auditory processing ability. The aims of the current study were to (a) determine personal FM effectiveness in children with confirmed APD; and (b) investigate a range of outcome measures, behavioral, electrophysiological, and questionnaires, to determine which, if any, show personal FM benefits.

MATERIALS AND METHODS

Study Design

A baseline-control design was used to determine whether personal FM systems were effective in improving auditory function. At visit 1, the children were tested with and without the FM system. Stability of the baseline was assessed at eight weeks when the children were retested with and without the FM. At the third visit, the children were reassessed following a five month trial period with a bilateral personal FM system used only in the classroom.

Participants

Participants consisted of 28 children with APD, 22 males and 6 females, aged 7 years 3 months to 12 years 9 months (mean age 9 years 6 months; standard deviation [SD] = 1 year 7 months). Participants with suspected APD were recruited via educational psychologists, learning disability tutors, other audiologists, teachers, developmental pediatricians, or speech-language pathologists. All participants were required to have normal pure-tone thresholds (screened at octave frequencies from 250 to 8000 Hz at 15 dB HL in a double-walled sound-proof room), normal type A tympanograms, and present ipsilateral and contralateral acoustic reflexes, bilaterally, to proceed with testing.

The diagnosis of APD was confirmed based on test performance for frequency pattern, dichotic digits, and gaps in noise tests, and a test of monaural low redundancy (compressed and reverberated words [CRW]) falling either two standard deviations below the mean on two tests or two ears of a single test, or three standard deviations below the mean on one test or one ear in the auditory processing test battery, consistent with ASHA (2005) criteria.

Participants' scores for the frequency pattern test (FPT), DDT, and CRW were compared with New Zealand normative data (Kelly, 2007). Other test results were compared with published norms. Before being assessed, participants' parents/guardians completed a comprehensive case history. Seven of the children (24%) in the APD group had no other related diagnoses, four had been previously diagnosed with autism spectrum disorder (specifically, Asperger syndrome), 16 were diagnosed with learning or language disability (this subset includes dyslexia), and eight were diagnosed with ADHD. Several children had multiple diagnoses.

A range of tests were selected to evaluate nonverbal intelligence quotient, short-term memory, reading, and attention, and, when appropriate, to set exclusionary criteria. The Test of Nonverbal Intelligence, Third Edition standard scores for participants in the APD group ranged from 80 to 138 (mean = 100.9, SD = 12.7). Potential participants were excluded from the study if their Test of Nonverbal Intelligence, Third Edition scores were <80 and were referred for an Educational Psychology evaluation. Clinical Evaluation of Language Fundamentals-Fourth Edition (CELF-4) Forward Digit Span standard scores ranged from 3 to 14 (mean = 7.96, SD = 2.85). Nine children in the APD group had digit span scores >1 standard deviation below the mean; these children had nonverbal intelligence quotient scores ranging from 89 to 121. Wheldall Assessment of Reading Passages reading scores (words read fluently and accurately per minute) ranged from 14 to 187 (mean = 75.32, SD = 49.47). Madelaine and Wheldall (2002) reported mean Wheldall Assessment of Reading Passages scores ranging from 105 (SD = 27.87) to 147 (SD = 22.30) for average readers aged 7–12 years.

Hearing and Auditory Processing Assessments

Behavioral Auditory Processing Measures

For each of the three visits (baselines 1 and 2, and post-intervention), assessments were conducted over 2–4 sessions, each lasting about two hours each. More sessions were required for some children to keep them motivated and on task. Auditory processing assessments were conducted in a double-walled sound-proof test room. Stimuli were presented via a calibrated Grason Stadler GSI-61, a two-channel clinical audiometer. Speech recognition scores in quiet were determined for CVC words presented at 60 dB HL to left and right ears in a counterbalanced order (10 words, 30 phonemes per ear). With the exception of the speech-in-noise test that was delivered via loudspeakers, all other test stimuli for the APD assessments were presented at 60 dB HL using Microsoft Windows Media Player on a desktop computer connected to a GSI-61 clinical audiometer with ER3A insert earphones. Oticon Bass reflex soundfield speakers were used for the speech-in-noise test.

Behavioral auditory processing measures were selected to assess a variety of auditory processing abilities (temporal processing, dichotic listening, binaural interaction, and monaural low redundancy) using a test battery that included items with low linguistic loading. A summary of all of the tests of auditory processing is found in Table 1.

Administration of these tests is described in detail in Sharma et al (2009). In addition to these standardized behavioral tests, two tests of monaural, low-redundancy were utilized. For the CRW test, ten CVC words (Nittrouer and Boothroyd, 1990), recorded with a male native New Zealand speaker (Purdy et al, 2000) and compressed (65%) and reverberated (0.3 sec), were presented to each ear. To digitally simulate 65% compression and 0.3 sec of reverberation, the CVC track lists were compressed to 45% their original length (65% compressed), using Adobe Audition 1.5 software. The time stretch effect was employed using a ratio of 181.818, high precision (hiss reduction), and a splicing frequency of 56 Hz with 0% overlap. A silent interval of 1.5 sec was inserted between each carrier word ("say") plus CVC word presentation. Both channels were selected, and the Adobe Audition 1.5 full reverb effect was applied using the following settings: total length 300 msec, attack time 2 msec, diffusion 10 and perception zero (i.e., no simulation of room irregularities). The mixing characteristics were set as follows: original signal (dry) 100%, early reflections 33%, and reverb 33%. This created a stereo waveform of CVC words lists, in which both channels were 65% compressed with a 0.3 sec reverberation time.

In addition to the CRW monaural, low-redundancy test, listening in noise was assessed in the soundfield using a four-speaker array. For this speech in spatial noise (SSN) test, the loudspeakers were positioned so that the center of each speaker was one meter high and located one meter from the center of the child's chair. Words from the Lexical Neighborhood Test (Kirk et al, 1995; Eisenberg et al, 2002) were rerecorded with a native New Zealand female speaker and were presented via the loudspeaker at zero degrees azimuth. Multitalker speech babble was presented simultaneously via a custom-built mixer through the three other speakers located at 90°, 180°, and 270° azimuth.

Table 1. Description of Behavioral Auditory Processing Assessments

Test	Test Subjects	Presentation Level	Stimuli	Presentation Mode	Auditory Process Assessed	Task
FPT	n = 28	60 dB HL	880 Hz (low) or 1122 Hz (high) tones	Monaural; insert earphones	Temporal processing	Repeat pattern of three tones (high and low)
DDT	n = 28	60 dB HL	Digits 1–10 (with exception of 7)	Binaural; insert earphones	Dichotic listening (binaural integration)	Repeat four numbers
GIN	n = 28	60 dB HL	6 sec broadband noise segments containing 0–3 silent intervals; gap durations ranging from 2 to 20 msec	Monaural; insert earphones	Temporal processing	Press the response button during brief periods of silence
500-Hz tone in white noise MLD	n = 20	60 dB HL	Bursts of narrow band noise within which a series of five tone pulses may or may not be present	Binaural; insert earphones	Binaural interaction	Respond when tone pulses are heard within the noise
CRW	n = 22	60 dB HL	10 CVC words with 65% compression and 0.3 sec reverb.; male speaker	Monaural; insert earphones	Monaural low redundancy	Repeat the word after the carrier phrase
SSN	n = 28	70 dB SPL at 0 dB SNR	Words from lexical neighborhood test list; female speaker; multitalker speech babble	Sound field speakers	Binaural low redundancy	Repeat the word

This configuration was designed to simulate a difficult classroom listening condition. Seven seconds of a 100-talker babble recording (http://spib.rice.edu/spib/data/signals/noise/babble.html) with minimal amplitude variation was selected and looped to generate several minutes of babble that was presented continuously. The lexical neighborhood test includes four "easy" and four "hard" lists of 15 words that were presented. Easy words are words that are frequently heard with few lexical neighbors while the hard words are infrequently heard with many lexical neighbors (Eisenberg et al, 2002). The test was performed in two listening conditions, with and without an FM system (bilateral open-fitted personal FM receivers and transmitter). The FM system was specifically selected for this study because of the open-fitted ear pieces. Fifteen "easy" words and 15 "hard" words were presented in the sound field at 70 dB sound pressure level (SPL) at a 0 dB SNR while the child listened with the FM systems on or off, in randomized order. List order was counterbalanced across test sessions and across children. For the FM-on condition, the teacher's microphone was taped to the front speaker, 1.5″ from the top of speaker and 3–4″ from the loudspeaker cone (as recommended in AAA [2008] guidelines), and was set to the directional microphone setting. The receivers were set to the middle volume setting (12 o'clock on the dial) for all testing. This was also the recommended setting for daily use, and the children were instructed not to alter this setting. The personal FM system consisted of a Phonak Campus S FM transmitter with a MiniBoom microphone (lapel microphone with directional and omnidirectional capabilities) and bilateral EduLink FM receivers. The EduLink receivers had a volume control range of zero to 15 dB. The volume control was set at the middle position, as recommended by the manufacturer, which was a comfortable level for all the children in the study. The output limiting was set to the default level of 95 dB SPL with a maximum operating range of 45′ (15 m). The audio frequency response of the Phonak Hearing Systems receivers is 200–6000 Hz. The SNR of the system is 45 dB SNR in full quieting mode, which means that the transmitter and the receiver are very close to one another; this value is the system's electroacoustical SNR. In practice, the SNR is influenced by distance and acoustical background noise. In classroom conditions, the SNR at ear level will typically be 15 or 20 dB; but as this is dependent on background noise levels, output setting, and volume setting, the SNR can be higher or lower than this range (Hans Mulder, personal communication, July 16, 2008). SNR of the FM systems was not directly measured for the individual participants. Data logging was not available in the FM systems used for the research.

Cortical Auditory Evoked Potentials

In addition to behavioral tests, speech-evoked cortical auditory evoked potentials (CAEPs) were recorded in quiet and with background noise present, with and without the FM systems worn and switched on, in a randomized order. For the FM conditions, the microphone was set to directional and placed in the center of the frontal speaker, and the child wore the bilateral open-fitted FM receivers. For the noise conditions, white noise produced by a custom-built white noise generator was presented continuously at 57 dB SPL (+3 dB SNR) via a custom-built mixer to two Turbosound IMPACT 50 loudspeakers positioned at 45° azimuth on the right and left side of the participant. The +3 SNR was selected based on previous studies of speech-evoked CAEPs in noise that used SNRs of 0 and 5 dB (Cunningham et al, 2001; Warrier et al, 2004) and based on the range of SNRs found in classrooms (Larsen and Blair, 2008). The speech stimulus was a 158 msec/da/spoken in isolation by a female talker. This stimulus was presented using STIM software and hardware at 60 dB SPL with an interstimulus interval (ISI, stimulus offset to stimulus onset) of 910 msec, via an Australian Monitor Synergy SY400 power amplifier and Sabine Graphi-Q GRQ-3102 equalizer to a Turbosound IMPACT 50 loudspeaker positioned at zero degrees azimuth, 1.5 m from the child's head position. The speech stimulus and white noise were calibrated using a half-inch polarized condenser free-field microphone connected to a Bruel and Kjaer measuring amplifier and oscilloscope. The RMS level of the speech sound was measured using linear weighting and the impulse response setting on the measuring amplifier.

Neuroscan 4.3.1 software and hardware and SynAmps amplifiers were used for evoked potential recordings. Evoked potentials were recorded in continuous mode (filter 0.01–100 Hz) via disposable Ag/AgCl Cleartrace Conductive Adhesive Gel ECG electrodes placed at Fz and Cz with a reference electrode on the right earlobe and the ground on the forehead. Eyeblinks were recorded via an active electrode above the right eye, referenced to the right earlobe (Kraus et al, 1993). The artifact rejection setting of ±100 μV ensured all eyeblinks were rejected; this was confirmed with visual inspection of individual electroencephalogram (EEG) recordings. EEG epochs with a −100 msec prestimulus to +600 msec poststimulus time windows were extracted from the continuous files. EEG epochs contaminated by eyeblinks producing voltage variations exceeding ±100 μV were rejected. Before averaging, the EEG epochs were baseline corrected using the prestimulus period and digitally low-pass filtered at 30 Hz (24 dB/octave slope).

During testing, participants watched a DVD movie of their own choice with the sound muted and subtitles on. They were instructed to stay alert and attend to the DVD rather than the stimulus being presented. Because of the age range of the subjects, peak identification involved first examining the overall morphology of the waves to see if the adult-like P1-N1-P2-N2 pattern had emerged or if the waveform was more consistent with the dominant P1 and late N2 that is typical of early childhood (Ponton et al, 2000) (see individual examples in Figure 1). The more adult-like bifid waveform was more evident for older children, but was not seen consistently. Eight participants (36%) aged 9.9 years on average (SD = 1.8 years) had CAEP waveforms with this bifid appearance. Participants with a single P1 peak were younger on average (9.3 years, SD = 1.8). This group contained fewer females (93% male) than the group with bifid CAEP waveforms (63% male).

When there were two well-formed peaks, and the waveform had clearly identifiable P1-N1-P2-N2 peaks, the earlier peak was identified as P1. If the adult pattern was present, P1 was identified as the largest positivity in the latency range 50–150 msec; this range was widened to 50–200 msec for waveforms with a single P1 peak. N2 was identified as the largest negativity in the latency range 200–400 msec. For peaks to be identified, both electrode montages, Fz and Cz, had to show the same pattern. When there was a single large peak without an identifiable N1, the amplitude was taken as the highest point in the waveform and the latency was taken as the center of the peak. All peaks were independently picked by two experienced electrophysiologists.

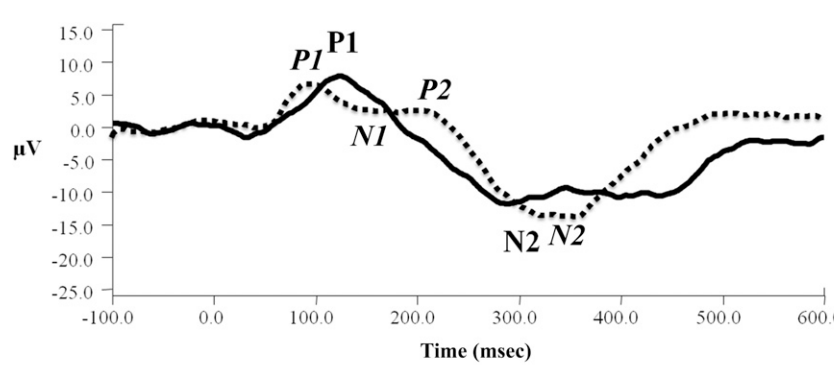

Figure 1. Individual CAEP waveforms for two participants with a single P1 peak (solid line, male aged 7 years 5 months) and a bifid P1-N1-P2 peak (dotted line-labels in italics, aged 8 years 8 months) recorded at Cz for the FM condition in quiet.

When there was a disagreement, a third opinion was sought by an experienced electrophysiologist who was blind to the stimulus conditions.

Questionnaires

The Listening Inventory For Education-United Kingdom version (LIFE-UK) student, version A, and the LIFE-UK teacher preintervention were administered before the fitting of the personal FM system. The LIFE-UK student version was completed with the researcher. One child was reluctant to complete the LIFE-UK student version before his FM fitting and his data were excluded. LIFE-UK teacher questionnaires were returned before the FM fittings to prevent teachers from referring back to when completing the follow-up questionnaire. Two open-ended questions were given to parents to complete before the FM system trial. These questions were (a) In the past two months, has your child had any difficulties in school or at home?, and (b) In the past two months, has your child had any listening difficulties at home or affecting his/her school work?

The LIFE-UK student, version A, and the LIFE-UK teacher were readministered following the trial of the personal FM system. The LIFE-UK student version was completed with the researcher. The LIFE-UK teacher questionnaires were given to teachers three weeks before the end of the trial period to allow ample time for completion. The two open-ended questions were readministered to parents following the FM system trial. In addition to these questions, six LIFE-UK teacher postintervention questions were selected and modified for parents (Appendix) based on their relevance to listening situations most likely to occur in the home setting. Parents were also asked to report any perceived positives or negatives or benefits perceived after the FM trial.

FM Intervention

Participants received a 20-week (two-school term) trial with a bilateral personal FM system. All children were fitted in week 1 or 2 of the school term. FM system fitting appointments were scheduled for one hour and were conducted at the child's school with the child, parent(s), and teacher(s) present and actively involved. The child was taught how to put the receivers on to his/her ears, how to use the volume control, how to change the batteries, and how to change the wax guards. The children were told to set the volume dial directly in the middle (or at 12 o'clock). They were instructed to leave the volume dial on that setting for the duration of the trial. The children were told to wear their personal FM systems at school during their core content courses (English, math, science, and social studies). They were not permitted to use the FM system after school or at home for the duration of the research study. Parents and teachers were also required to understand how the open-fitted ear pieces work so that they could assist with trouble-shooting if required. They were instructed on how to use the transmitter, how to wear the microphone, and how to charge the system. In addition to the verbal, hands-on, training parents and teachers received a one-page summary of important reminders related to the FM system and the principal researcher's contact details and were encouraged to call or e-mail with any questions or problems. The researchers also called the parents half-way through the trial period in an attempt to identify and address any problems with the FM systems that may not have been reported.

Post-FM System Trial

Following the 20-week trial with the personal FM systems, the student, parent, and teacher versions of the LIFE-UK questionnaire were readministered and the participants were reassessed using a range of behavioral measures of auditory processing and CAEPs. Outcome measures included CRW, gaps in noise (GIN), FPT, DDT, masking level difference (MLD), SSN, CAEP latencies and amplitudes, and auditory and visual attention measured using the integrated visual and auditory-continuous performance test (IVA-CPT) (Sandford and Turner, 1995). The results were examined to determine whether there was stable test–retest performance during the baseline period, before determining whether they could be used to assess the impact of the FM intervention. Repeated measures analyses of variance were performed with visit, test ear (where appropriate), and test condition (where appropriate) as within-subject factors.

RESULTS

Summary

Overall, the behavioral data showed no consistent change in scores across visits for CRW, MLD, and sustained attention scores. Several measures showed practice effects and no intervention effect (GIN, DDT, and SSN hard words). FPT and SSN easy words showed stable baseline scores and statistically significant improvements after the FM intervention. The CAEP results show a clear impact on noise and FM use, and there were some changes in CAEPs across visits, but these occurred during the baseline as well as the intervention period, and hence cannot be attributed to the FM trial. Questionnaire results indicated significant improvements in the children's and teachers' ratings of listening behavior after the FM trial.

Behavioral Auditory Processing Measures

Repeated measures analyses of variance were performed to determine the effects of visit (×3), test ear (×2 for FPT,

Table 2. Mean Scores (1 SD Shown in Parentheses) Obtained on the Auditory Processing Assessments for the 28 Children with APD Who Completed the Study

		Ear/Condition	Baseline 1	Baseline 2 (+8 Weeks)	Post-FM (+28 Weeks)	Significant Effects
FPT N = 28	%	Left	37.12 (25.41)	39.28 (27.04)	58.32 (29.24)	Age
						$F(1,25) = 12.66$, $p = 0.002$
		Right	42.33 (25.77)	37.62 (23.94)	56.66 (28.26)	
DDT N = 28	%	Left	75.00 (13.88)	78.31 (14.86)	83.66 (10.35)	Age
		Right	84.11 (11.04)	87.41 (9.75)	89.29 (10.97)	$F(1,25) = 13.43$, $p = 0.001$
						Visit × ear
						$F(2,50) = 5.94$, $p = 0.005$
						Visit × ear × age
						$F(2,50) = 5.51$, $p = 0.007$
GIN N = 28	ms	Left	6.57 (4.15)	5.04 (1.26)	4.36 (0.73)	n.s.
		Right	5.61 (2.42)	4.96 (1.26)	4.29 (0.76)	
	%	Left	66.85 (13.79)	75.24 (7.60)	79.46 (5.77)	Visit
		Right	69.70 (12.75)	71.90 (9.27)	79.88 (5.22)	$F(2,50) = 5.68$, $p = 0.006$
CRW N = 22	%	Left	51.00 (16.58)	52.61 (10.45)	54.39 (8.83)	n.s.
		Right	54.95 (12.11)	56.82 (11.10)	52.82 (10.14)	
SSN N = 28	%	Easy words no FM	75.96 (15.64)	74.04 (11.68)	82.86 (8.20)	Age
		Easy words with FM	90.68 (8.16)	89.76 (8.20)	92.61 (6.62)	$F(1,25) = 8.24$, $p = 0.008$
		Hard words no FM	65.47 (15.86)	72.38 (14.71)	73.81 (13.44)	Gender
		Hard words with FM	81.41 (10.29)	85.94 (10.15)	86.90 (10.01)	$F(1,25) = 14.83$, $p = 0.001$
						FM
						$F(1,25) = 6.80$, $p = 0.015$
Sustained attention	SS	Auditory N = 27	70.74 (36.11)	72.85 (42.35)	70.93 (43.69)	n.s.
		Visual N = 23	81.91 (22.99)	81.83 (31.53)	86.09 (31.59)	
MLD N = 28	dB		13.55 (1.70)	14.11 (2.04)	14.11 (1.50)	n.s.

Notes: Post-FM results were obtained after a 20-week trial of bilateral personal FM systems. The number of participants with complete data for all three visits is shown for each assessment. The CRW test was not completed on the first six children and hence the number of participants is reduced for the CRW. Not all children could reliably complete the sustained attention task; results are shown for participants who completed the sustained attention task sufficiently well to generate a standard score. n.s. = not significant; SS = standard scores.

DDT, CRW, and GIN), and test condition (×4 for SSN, FM versus no FM and "easy" versus "hard" words; ×2 for IVA-CPT, visual versus auditory attention) on assessment results. Age and gender were included in these analyses as covariates. Average results for these assessments for the three visits are summarized in Table 2, and significant analysis of variance (ANOVA) results are listed. There were no statistically significant effects for CRW, MLD, GIN thresholds (in msec), or IVA-CPT sustained auditory or visual attention scores. Percentage correct GIN scores did show a significant visit effect, improving systematically across visits from 68.3% to 73.6% to 79.7% for visits 1, 2, and 3, respectively. The improvement in scores was 5–6% between visits 1 and 2 during the baseline period, and between visits 2 and 3 (before versus after the FM intervention). This indicates a practice rather than an intervention effect. The GIN threshold values listed in Table 2 also show evidence of a practice effect, but these differences were not statistically significant, presumably because of the large variance in the visit 1 gap threshold data. In general, both GIN threshold and percentage correct scores showed reduced standard deviations and improved scores across visits, consistent with a practice effect. Therefore the FPT, DDT, and SSN behavioral tests were the focus of additional statistical analysis.

FPT

As expected, participant age did have a significant effect on FPT scores. A correlation analysis showed that average baseline FPT scores for the left and right ears were positively correlated with participant age ($r > 0.52$, $p = 0.004$). Individual ear FPT scores are plotted in Figure 2 for the three visits. Although the ANOVA showed no overall effect of visit on FPT scores, Figure 2 shows consistent scores for the two baseline assessments and an improvement of approximately 20% in FPT scores after the intervention. Planned comparisons showed that this improvement was statistically significant for the right and left ears when visits 2 and 3 are compared ($p < 0.001$), and for the right ($p = 0.010$) and the left ($p < 0.001$) ears when visits 1 and 3 are compared. Visits 1 and 2 scores did not differ for either ear ($p \geq 0.155$). Thus, FPT scores did not show a practice effect and improved significantly after the FM intervention in both ears. The majority (93%) of individual

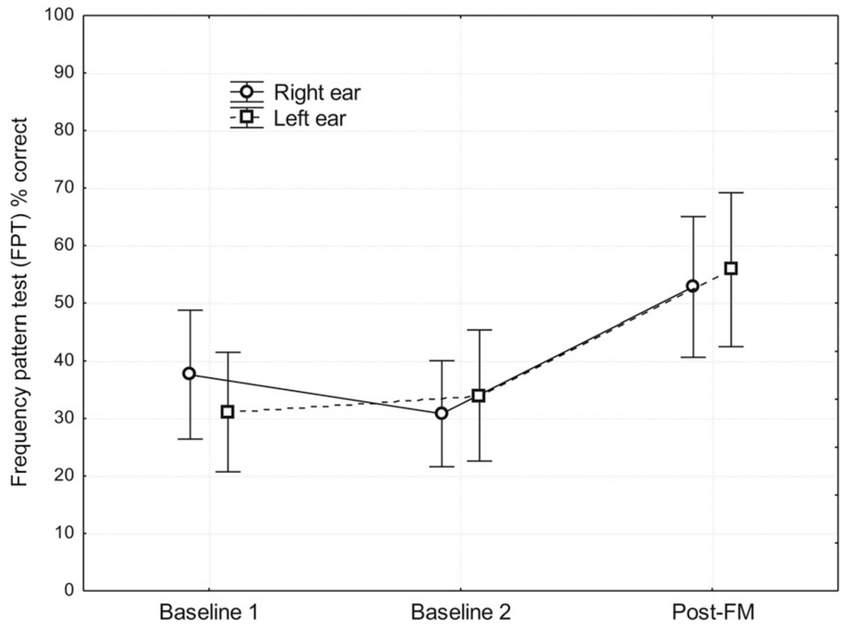

Figure 2. Average FPT scores (N = 28) for the two baseline measurements (0 and +8 weeks) and the post-FM visit. Error bars show 95% confidence intervals.

participants showed improved FPT scores at the end of the intervention phase.

Dichotic Digit Test

DDT scores were also affected by participant age, and there were significant interactions between ear and visit, and between ear, visit, and age. Average baseline DDT scores for the left and right ears were positively correlated with participant age ($r > 0.44$, $p \leq 0.019$). Figure 3 shows average DDT scores for left and right ears across the three visits. Left ear DDT scores improved slightly across the three visits, whereas right ear DDT scores improved between baseline visits 1 and 2 and did not change between visits 2 and 3. Planned comparisons showed that right ear DDT scores improved significantly between visits 1 and 2 ($p = 0.035$) and did not change between visits 2 and 3 ($p = 0.915$), consistent with

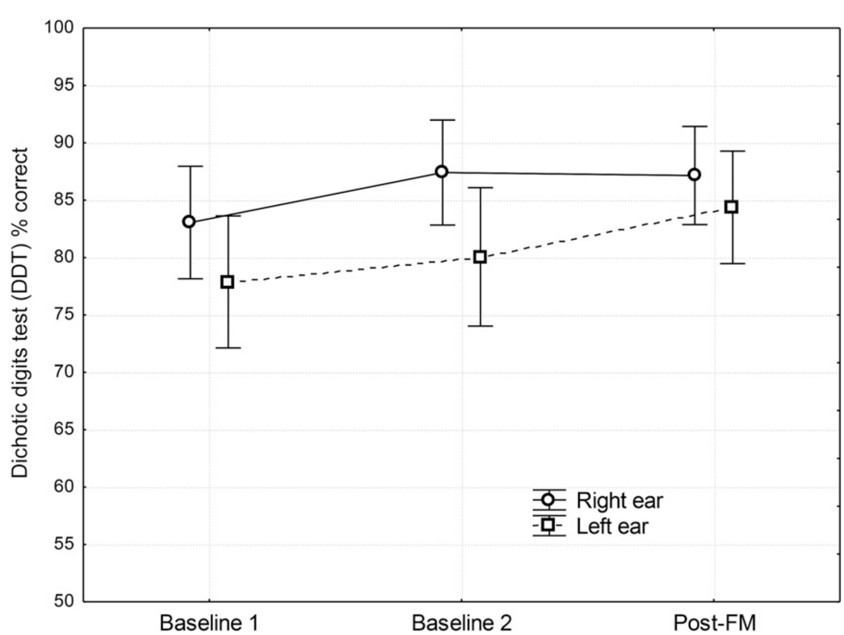

Figure 3. Average DDT scores (N = 28) for the two baseline measurements (0 and +8 weeks) and the post-FM visit. Error bars show 95% confidence intervals.

a practice effect. For the left ear, the scores improved on average by approximately 3% and 5% between visits 1 and 2, and between visits 2 and 3, respectively. Planned comparisons showed that this change was not significant for baseline visits 1 versus 2 ($p = 0.415$), but was significant for visits 2 versus 3 ($p = 0.034$). Although this suggests an intervention effect for DDT left ear scores, the evidence for this is not strong since the right ear did not show an intervention effect (and the participants wore an FM system in both ears), and the improvement in scores did not differ greatly from the practice effect evident in the baseline scores. This difference in apparent practice effect between the two ears could be due to the left ear having a lower level of performance initially.

SSN Test

Age, gender, and FM effects on SSN scores were significant. As was seen for FPT and DDT scores, SSN scores improved significantly with age. SSN scores averaged across baseline visits were not correlated with participant age, indicating that the effect of age on SSN scores was not substantial. This is evident when SSN scores are averaged across baseline conditions; the 7–9 years olds (N = 15) scored 78.2% (SD = 4.7) and the 10–12 years olds scored 81.4% (SD = 5.4). The gender effect on SSN scores reflects the lower scores overall of the six female participants compared with the male participants (77.2% for girls, 82.0% for boys). Although there was no overall effect of "easy" versus "hard" words, Table 2 shows that the scores were generally lower for the "hard" words (by 5.7% on average). This is illustrated in Figure 4, which shows SSN scores for FM and no-FM conditions for the three visits, and for easy versus hard words. There was a substantial improvement (13% on average) in SSN scores on each test occasion when the participants wore the FM systems. Average scores for easy words were very consistent between visits 1 and 2, but improved by about 7% after the FM intervention. Planned comparisons confirmed these findings. For easy words, there was no difference in visit 1 versus 2 baseline scores ($p = 0.763$), but SSN scores improved significantly between visits 2 and 3 with $p = 0.005$. For hard words, the difference between visit 1 and 2 scores approached statistical significance ($p = 0.056$), and scores for visit 2 and 3 did not differ ($p = 0.732$). This consistency in baseline SSN easy word scores and improvement after the FM intervention is shown in the left hand panel in Figure 4. In contrast, scores for the hard words showed a different pattern, with a practice effect evident between visits 1 and 2 and no change after the intervention. Thus, the SSN data show an immediate beneficial effect of the FM systems on speech perception in noise, measured in laboratory conditions, and also show a longer-term beneficial effect of using the FM systems on speech scores, but for the easy words only. Although statistically significant, the SSN score improvement after the FM trial was only evident in 68% of individual participants.

Cortical Auditory Evoked Potentials

Overall, the CAEP analysis did not show changes in amplitudes or latencies that could be attributed to the use of the FM system. Grand average CAEP waveforms are shown in Figure 5. The waveforms show the characteristic pattern of young school-aged children, with a broad positivity (labeled here as P1) and a late negativity (labeled as N2), with latencies of approximately 100–150 msec and 250–300 msec, respectively. A bifid peak was apparent in some individual children; thus, for some children, it would be possible to label P1-N1-P2-N2 peaks. Since N1 was not reliably identified in all children, however, only P1 and N2 were analyzed. Repeated measures ANOVAs were undertaken to examine within-subject effects of the following factors on P1 and N2 latencies and amplitudes: electrode montage (Cz-A2, Fz-A2), visit (two baseline and one post-FM), FM (with and without FM), and noise (quiet and noise at +3 dB SNR). Because of equipment difficulties, complete CAEP data were not available for six children; thus, CAEP analyses are based on the results of 22 children. A summary of the CAEP statistical analyses can be seen in Table 3.

P1 latencies showed significant effects of noise [$F(1,21) = 90.63$, $p < 0.001$], and a significant noise by FM interaction [$F(1,21) = 21.90$, $p < 0.001$]. As illustrated in Figure 6, P1 latencies were consistently longer in noise than in quiet; however, the difference between noise and quiet conditions was reduced for the FM condition. Without the FM, P1 latencies were, on average, 12.8 msec later in noise versus quiet. With the FM, this difference between quiet and noise conditions was considerably reduced, to 4.9 msec on average. Thus, noise had less impact on P1 latencies when the participants were wearing the FM system. There were no statistically significant findings for P1 amplitudes.

N2 latencies showed significant effects of visit [$F(2,42) = 7.44$, $p = 0.002$], FM [$F(1,21) = 5.07$, $p = 0.035$], and noise [$F(1,21) = 4.54$, $p = 0.045$]. As was seen for P1, N2 latencies were significantly longer in noise and shorter for the FM conditions. Thus, the impact of the noise was reduced by the FM system. The visit effect resulted from an increase in N2 latencies at baseline visit 2 compared with visit 1. N2 latency increased significantly ($p < 0.001$) from 294 msec (SD = 28.0) on average at baseline visit 1 to 313 msec (SD = 40.8) at baseline 2. This visit effect on N2 latency resembles a "practice effect" since results differ across baseline visits but do not differ ($p = 0.362$) between visits 2 and 3 (post-FM average 308 msec, SD = 39.0 msec).

N2 amplitudes showed significant effects of electrode montage [$F(1,21) = 5.42$, $p = 0.030$], visit [$F(2,42) = 4.09$,

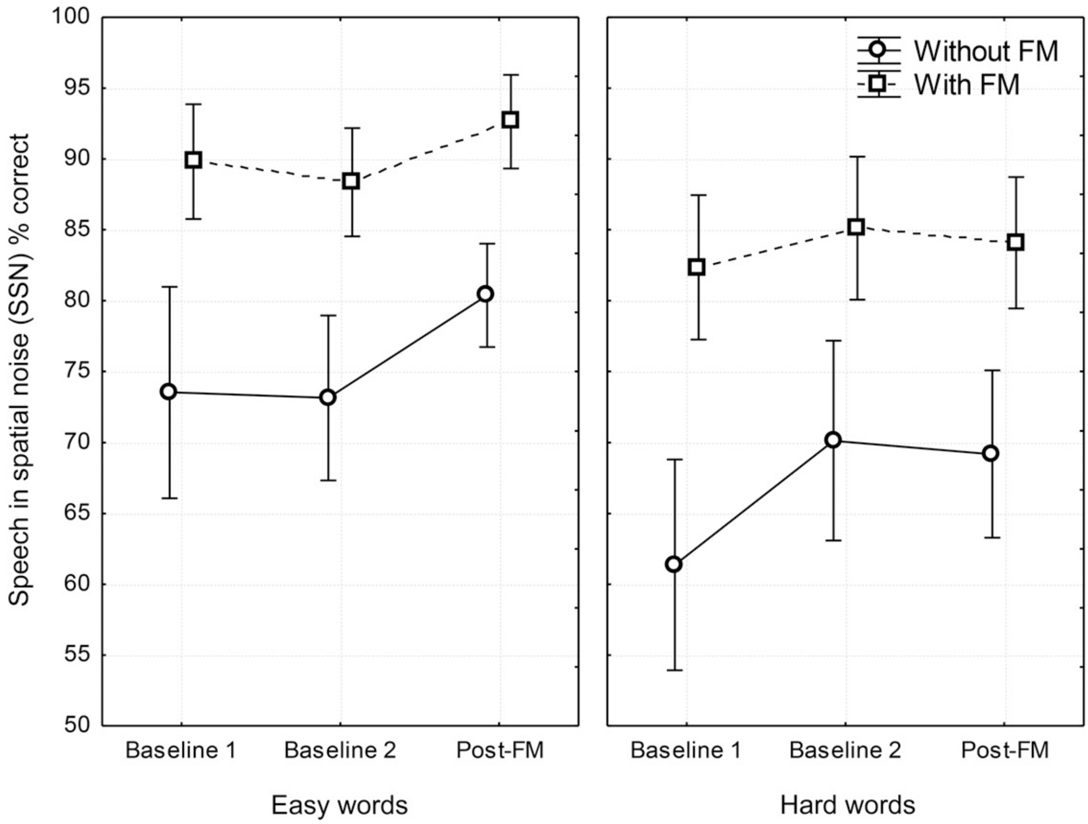

Figure 4. Average SSN scores (N = 28) for the two baseline measurements (0 and +8 weeks) and the post-FM visit. For the "With FM" condition, participants wore bilateral FM systems while listening to SSN words with the FM microphone placed near the loudspeaker delivering the words. Scores are shown separately for easy and hard lexical neighborhood test words. Error bars show 95% confidence intervals.

$p = 0.024$], and noise [$F(1,21) = 97.87, p < 0.001$], and a significant interaction between noise and FM [$F(1,21) = 64.42, p < 0.001$]. The electrode montage effect resulted from a small N2 amplitude advantage [i.e., N2 amplitude was larger (better) at Cz] at Cz (−8.45 μV, SD = 3.91) compared to Fz (−8.05 μV, SD = 3.71). The visit effect resulted from an overall reduction in N2 amplitudes across the three visits. It is not possible to determine whether there is an effect of the FM trial on N2 amplitudes as N2 reduced by a similar

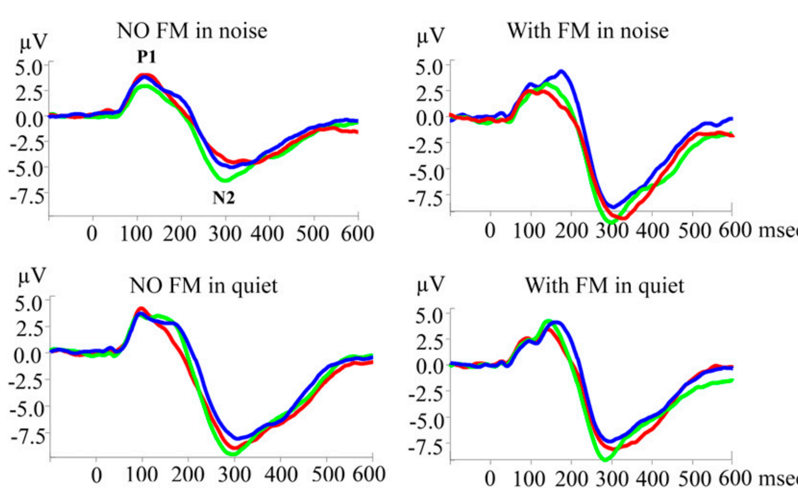

Figure 5. Grand average CAEP waveforms (N = 22) for baseline visits 1 (green) and 2 (red), and post-FM visit 3 (blue) for the four stimulus conditions, recorded at Cz. A larger positivity "P1" between 100 and 200 msec and a late negativity "N2" at 250–350 msec are evident in the waveforms. CAEP amplitudes are reduced for the "No FM in Noise" condition.

Table 3. Results of Repeated Measures ANOVA Statistical Analyses of CAEP P1 and N2 Latencies and Amplitudes

	P1		N2	
	Latency	Amplitude	Latency	Amplitude
Electrode montage (Cz-A2, Fz-A2)	Not significant	Not significant	Not significant	$F(1,21) = 5.42$, $p = 0.030$*
Visit (two baselines vs. one post-FM visit)	Not significant	Not significant	$F(2,42) = 7.44$, $p = 0.002$*	$F(2,42) = 4.09$, $p = 0.024$*
FM (with vs. without FM)	$F(1,21) = 21.90$, $p < 0.001$*	Not significant	$F(1,21) = 5.07$, $p = 0.035$*	$F(1,21) = 97.87$, $p < 0.001$*
Noise (quiet vs. noise +3 dB SNR)	Not significant	Not significant	$F(1,21) = 4.54$, $p = 0.045$*	$F(1,21) = 64.42$, $p < 0.001$*
FM by noise interaction	$F(1,21) = 90.63$, $p < 0.001$*	Not significant	Not significant	Not significant

Note: *significant.

amount between visits 1 and 2 and between visits 2 and 3. On average, N2 amplitudes were −8.82 μV (SD = 3.98), −8.25 μV (SD = 3.65), and −7.63 μV (SD = 3.82) at visits 1, 2, and 3, respectively. Standard deviations indicate similar variability across visits.

N2 amplitudes systematically decreased each time the children were tested. The CAEP waveforms in Figure 5 show that the reduction in N2 amplitude was associated with a broadening of the waveform and increased amplitude of the positive peak in the CAEP waveform at an approximate latency of 200 msec. Thus, the apparent change in N2 amplitude may reflect an increase in P2, rather than a reduction in N2.

Figure 7 illustrates the effect of noise and FM on N2 amplitudes, across the three visits.

These were reduced (less negative) in noise compared with the quiet condition and, as was seen for P1 and N2 latencies, FM reduced the impact of noise on N2

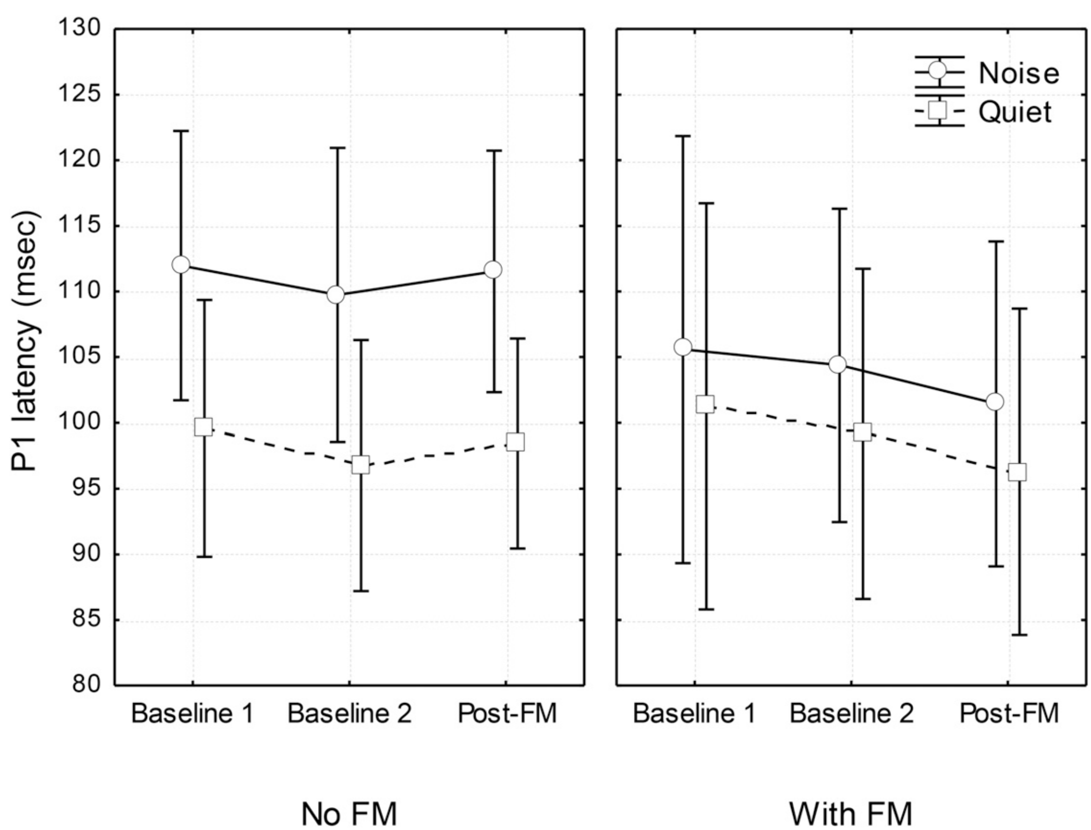

Figure 6. Average P1 latencies (N = 22) for the quiet and noise conditions, with and without FM, across the three visits (post-FM = visit following the five months trial period). Latencies were significantly longer in noise. The FM system reduced the impact of noise on P1 latencies. Error bars show 95% confidence intervals.

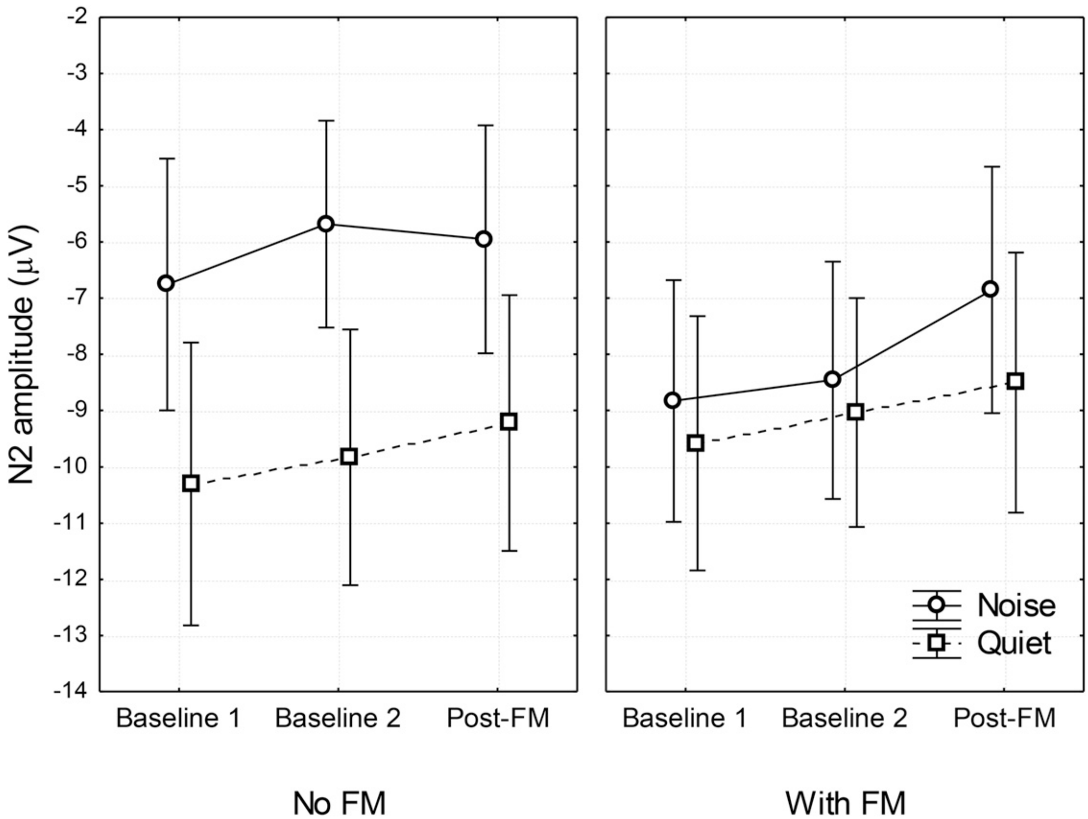

Figure 7. Average N2 amplitudes (N = 22) for the three visits (post-FM = visit following five months trial period) for the quiet vs. noise and FM/no FM conditions. There were significant main effects of visit and noise on N2 amplitudes. N2 amplitudes were smaller in noise than in quiet, but the impact of noise was reduced by the FM system. On average, amplitudes reduced across the three visits. Error bars show 95% confidence intervals.

amplitudes. Without the FM, N2 amplitudes were reduced by 3.66 μV on average when noise was introduced. With the FM, N2 amplitudes were less affected by noise; the reduction was only 0.87 μV on average. Although there were no interaction effects for N2 amplitudes, Figure 7 shows that the change in N2 amplitudes across visits was systematic for CAEPs recorded in quiet, irrespective of the FM condition, but varied across the FM conditions for CAEPs recorded in noise. Without the FM, N2 amplitudes show a pattern similar to that seen for P1, with a change across the baseline visits, and stable results between visits 2 and 3. With the FM for the noise condition, there is minimal change between baseline visits, but N2 amplitudes reduced after the FM trial. Planned comparisons showed these differences were not significant, however.

Questionnaires

Before and immediately after the FM trial period, teachers and children completed the LIFE-UK. Parents responded to two open-ended questions before the trial. Preintervention LIFE-UK ratings show that children in the APD group had greater classroom listening difficulties than a normative sample (N = 83) of New Zealand school children of the same age (Morgan, 2007). The mean rating for all 13 items in the LIFE-UK for the APD group in the current study (N = 27) was 2.70 (SD = 0.62). A z-test indicated a significant difference ($p < 0.001$) between the participants' LIFE-UK ratings and Morgan's normative sample (mean = 1.83, SD = 0.54). The higher ratings of the APD group in the current study indicate significantly greater self-rated listening difficulty than that reported by typically developing children of the same age.

After the intervention, the mean LIFE-UK rating for the children who completed both pre- and postquestionnaires (N = 27) was 2.40 (SD = 0.44). A paired t-test showed that the pre- versus post-FM difference was statistically significant ($t = 1.71$, $df = 26$, $p = 0.010$), indicating an improvement in the children's self-rated classroom listening ability after the FM trial. For the teachers, pre- and post-FM questionnaires are somewhat different, and hence it is not possible to compare the results directly. The pre-FM questionnaire consists of 11 items addressing classroom listening and behavior, and the teacher rates each item on a 5-point scale ranging from "very good" (=1) to "satisfactory" (=3) to "very poor" (=5). Average teacher ratings were 3.32 (SD = 0.67), indicating that, overall, listening and behavior fell between "satisfactory" and "poor" on the scale. The

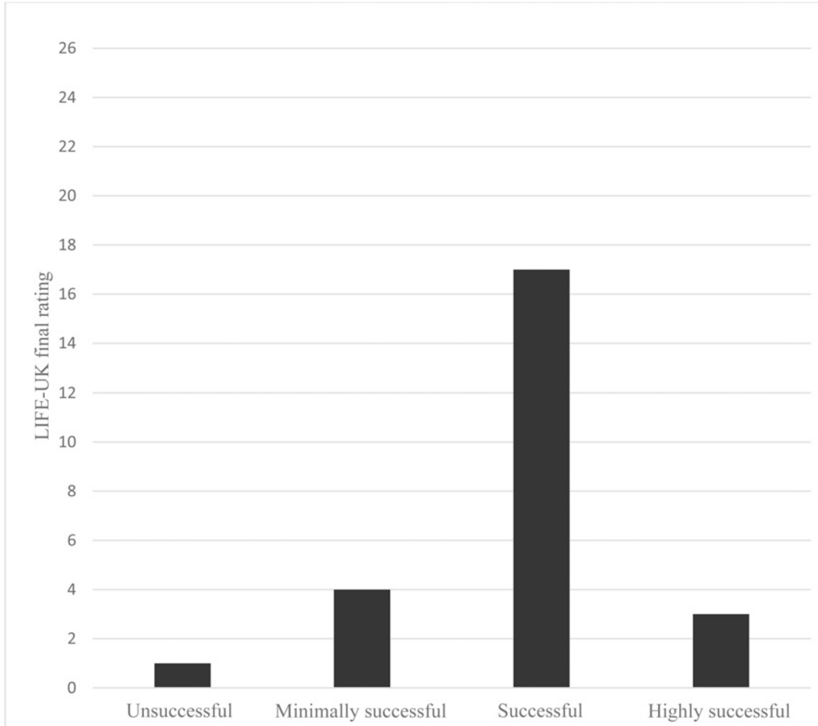

Figure 8. LIFE-UK post-FM trial teacher ratings following the FM trial.

postintervention questionnaire has 11 questions that the teacher responds to on a 5-point scale ranging from +2 "improvement" to 0 "no change" to −2 "deterioration." According to the LIFE-UK instructions, these 11 ratings are summed, together with the teacher's response to one final question: "Based on my knowledge and observations I believe that the amplification system is beneficial to the student's overall attention, listening and learning in the classroom." This final item has the same scale as the 11 previous items, but has a higher weighting as "improvement" is assigned +5 points and "deterioration" is assigned −5 points. FM success is categorized based on the summed points across the 12 items. The outcomes are described as Highly successful (20−27 points), Successful (10−19 points), Minimally successful (1−9 points), or Unsuccessful (<1 points). Postintervention summed LIFE-UK teacher ratings for the 27 teachers completing the questionnaire indicated that 74% of the FM fittings were "successful" (N = 17) or "highly successful" (N = 3).

Six children (22%) were rated by the teachers as "minimally successful" and one child (4%) was rated as "unsuccessful," see Figure 8. Reasons cited by the teachers for lack of success included multiple classroom teachers and equipment difficulties. Three teachers commented on the unsuccessful and minimally successful fittings as follows:

> "I felt the device was hugely successful initially as it was new and exciting. As [his] attitude changed (I can't instead of I can) he forgot to wear the device and even when wearing it his attitude let him down.";

> "For [him] it was only effective when oral testing when class noise levels were very low. [He] reacts slowly to change so did not respond to someone else using the equipment (e.g. the receiver).";

> "Found it difficult at times with teacher's earpiece (was quite irritating). Also many specialist teachers took lessons so the usage was not consistent throughout the day. I felt the concept was great - with an excellent demonstration given on how to use the FM. However, the practicalities of the classroom use by the teacher and pupil were often difficult and cumbersome."

Some written comments from the teachers with successful fittings were as follows:

> "In general - there has been an improvement in his behaviour re: instruction, listening, processing and executing his tasks.";

> "Really improved [his] overall attention span and participation in class."; "[He] has become significantly more focused during the last two terms [trial period]."

The following are several examples of parents' comments about their children's listening difficulties before the FM fitting:

> "We have to explain in detail when learning new things. . . . she has trouble when we give her multiple instructions."

> "We do have to repeat sentences. . . .Recall not good."

> "...has great feelings of not being able to do things and he gives up. Also at home he has great trouble hearing me if there is lots of noise."

> "...says he doesn't hear people talking, if at the back of the classroom he doesn't hear the teacher. On holiday he complains if the radio is on."

Parents' comments indicated that they had good insight into their children's listening and learning difficulties. After the FM trial, parents completed a six-item questionnaire based on the LIFE-UK teacher questionnaire, rating their children's listening ability and behavior on a 5-point scale similar to that used by the teachers (+2 = "improvement," 0 = "no change," −2 = "deterioration"). Average ratings (N = 28) were 0.95 (SD = 0.69), indicating an overall improvement. Examples of parents' comments from those who were positive about the FM trial are as follows: "Useful tool in the classroom situation"; "[Her] confidence has increased. [She is] not as tired after school"; "[She] has found that lesson instructions are much easier to understand, she is able to start [her] work immediately now."; "I believe it is an excellent tool to make the focus of learning on the learner! Also the teacher is more aware of the student." Parents with negative experiences commented as follows regarding perceived benefit: "...as parents it is hard to know the benefits in the classroom"; "Not always working...Too many teachers involved." A Wilcoxon matched pairs test showed no difference between teacher and parent ratings (N = 25, $Z = 0.07$, $p = 0.943$).

DISCUSSION

The aims of the current study were to (a) further evaluate personal FM effectiveness in children with confirmed APD; and (b) determine which approaches, behavioral, electrophysiological, or questionnaires, will be effective for determining personal FM outcomes. The FM system is essentially providing an enhanced acoustic environment by improving the signal-to-noise ratio of the teacher's speech (a spectrally and temporally complex signal) at the child's ear.

The primary aim of this study was to determine whether a trial of personal FM for two school terms would be beneficial for children with APD, based on behavioral and electrophysiological measures of auditory processing and on questionnaire ratings by participants and their teachers and parents. Two auditory processing measures, FPT and SSN easy word scores, showed stable baseline results and a statistically significant improvement after the intervention. Questionnaire results from participants, parents, and teachers generally showed positive outcomes for the FM trial.

When participants wore the FM system during CAEP testing, the effects of noise were reduced, providing evoked potential evidence for the improved SNR. This effect occurred for all individual participants. CAEPs changed over the baseline and the FM trial period, and hence, we did not observe a physiological change that could be attributed to the use of the FM system.

Individual participants also consistently had enhanced SSN speech perception scores for the FM condition. Thus, it is possible to demonstrate the immediate benefit of an FM system for individual children using both objective and behavioral measures in the laboratory.

Friederichs and Friederichs (2005) found enhanced P2 amplitudes after a one-year trial of personal FM systems in a small group of children with ADHD and suspected APD, compared with a control group. The grand average waveforms shown in Figure 5 indicate a change in waveform shape over time in the P2 latency region for our participants. P2 was not clearly discernible in most participants' waveforms in the current study, however, and hence only P1 and N2 were analyzed. Two factors probably account for this difference between studies. First, participants in Friederichs and Friederichs' study were aged 7–14 years (mean = 10 years 0 months, SD = 1 year 9 months), whereas children in the current study were slightly younger (7–12 years, mean = 9 years 2 months, SD = 1 year 10 months). Older children aged 9+ years are more likely to have separable P1-N1-P2 peaks in the CAEP waveform (Ponton et al, 2000). Second, Friederichs and Friederichs used a much slower stimulus presentation rate (3,025 msec ISI versus 910 msec in the current study). Changes in ISI have more dramatic effects on the CAEP waveform in children than in adults (Imada et al, 1997; Gomes et al, 2001). At slow stimulus rates, young children have adult-like P1-N1-P2-N2 waveforms (Sharma et al, 2007). Slower stimulus repetition rates are recommended for future studies examining the effects of auditory experience in children, so that possible changes in N1, P2, and N2 would be more readily observable. Additional electrode locations for CAEP recordings are also recommended. Temporal lobe electrode sites are sensitive to differences in auditory processing across populations (Bellis et al, 2000) and hence may be more sensitive than midline electrode locations to the effects of auditory experience and training in people with APD. The contribution of CAEP information from different electrode sites to APD diagnosis and evaluation of treatment effects is a topic of interest for future studies. Parthasarathy and Bartlett (2012) found differential effects of electrode montage on evoked responses to amplitude-modulated stimuli in a study of age-related changes in auditory processing in Fischer-344 rats. Schochat et al (2010) found middle latency response amplitudes improved (increased) for certain electrode montages (primarily left hemisphere active electrodes) in their experimental training group of children with learning disability which made their MLR amplitudes more similar to the controls. Wilson et al (2013) review electrophysiological studies of auditory training outcomes in children with auditory processing deficits and conclude that there is limited evidence in this area. Further studies exploring evoked potential changes for a wider range of electrode sites may produce better evidence of changes in CAEPs, and may elucidate the optimal recording montage for clinical investigation of CAEPs in APD.

In the current study, N2 amplitudes reduced systematically across visits (i.e., became more positive), rather than showing a clear effect of FM experience. Thus, unlike Friederichs and Friederichs (2005), we did not find a clear pattern of enhanced CAEPs after the FM trial. The impact of maturational changes on CAEPs has been extensively investigated by Ponton et al (2000), from early childhood through to adulthood. Ponton et al noted that P2 latency changes little across midchildhood to adulthood; however, there are age-related "decreases" in P2 amplitude. N2 reaches maximal negative amplitude at age 10–11 years, and then becomes more positive.

An important outcome of the current study was the significant improvement in frequency pattern and speech perception (SSN easy words) after the 20-week trial of personal FM systems. Both these assessments showed good test–retest reliability in the baseline period. The FPT (Pinheiro and Ptacek, 1971) is widely used clinically for APD assessment (Emanuel, 2002; Bellis, 2003; Chermak et al, 2007), and hence, the finding of good test–retest reliability and sensitivity to intervention effects is reassuring. The FPT was originally validated by demonstrating its sensitivity to central auditory system lesions (Pinheiro, 1976), but studies have also demonstrated its sensitivity to APD in children with language and reading disorder (Pinheiro, 1977; Stollman et al, 2003; Sharma et al, 2006; 2009). The SSN test is a monaural, low-redundancy test developed for the current study, and hence it is not possible to directly relate the SSN findings to previous studies. Monaural, low-redundancy tests are widely used tests for evaluating central auditory function (Krishnamurti, 2007). The current findings suggest that the SSN, easy word lists, is a reliable measure of auditory processing and a sensitive test for evaluating FM effectiveness that warrants further investigation in a wider group of children. Embedding speech stimuli in noise is probably the most common method of reducing intrinsic redundancy when testing for APD (Bellis, 2003). The SSN differs from most clinical speech-in-noise tests in that the noise is spatially distributed around the listener, to better simulate classroom listening conditions.

In a recent study of frequency discrimination training in children, Halliday et al (2008) found that auditory learning can occur, in some children at least, after relatively limited training. As noted by Halliday et al, there has been a great deal of recent interest in auditory perceptual learning (see review by Moore and Amitay, 2007). Improved performance after discrimination training can continue over a prolonged period, but auditory learning can also be very rapid. Amitay et al (2006) found discrimination improvements within a single training session, and discrimination improved even when listeners were trained using identical stimuli, suggesting an important role for attention in auditory perceptual learning. Further research is recommended to determine whether the enhanced auditory signal provided by personal FM systems can accelerate or enhance the effects of auditory training in children with APD.

The success of personal FM systems is largely dependent on support within the school as well as the attitude of the students and their families to the devices. Only a modified version of the LIFE-UK has been used successfully to evaluate outcomes of sound-field amplification in a large study in the United Kingdom (Dockrell and Shield, 2012), but to our knowledge no previous publications have included the LIFE-UK when assessing personal FM outcomes. Participants in this study rated their classroom listening as significantly better after the FM trial. Parents and teachers were generally positive about the FM systems and gave similar responses on the post-FM questionnaire. In the current study, outcomes were only determined immediately after the conclusion of the 20-week FM trial, and hence, the long-term (sustained) benefits of personal FM use are not known. Further research is required to better determine the impact of FM systems on CAEPs, and to determine whether improvements in auditory processing abilities are associated with improved functional outcomes in the longer term, such as in the areas of literacy, expressive, and receptive language, and classroom participation and behavior.

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APPENDIX

Since your child started wearing the personal FM system have you noticed a change in the following behaviors?

(*Please tick the box consistent with the most appropriate response based on your observations for each question*)

	Improvement		No Change	Deterioration	
1. Following directions	2	1	0	−1	−2
2. Overall attention span	2	1	0	−1	−2
3. Willingness to answer questions	2	1	0	−1	−2
4. Answering questions in an appropriate and relevant manner	2	1	0	−1	−2
5. Overall attitude toward school	2	1	0	−1	−2
6. Overall fatigue	2	1	0	−1	−2

Note: Questions adapted from the LIFE-UK edition by David Canning 1999.