Auditory Processing Disorders II: experimental results on APD management with personal FM systems

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Abstract

In a first paper (Mülder, Rogiers and Hoen, the 6th~7th volume of Speech and Hearing Review), we have reviewed actual views on Auditory Processing Disorders (APD), their definition, etiology, diagnosis and the actual consensus on APD management strategies. In this second article, we proposed to report on recent experimental work done on the management of APD using environmental modifications via personal frequency modulation (FM) devices. This approach to APD management is based on the assumptions that the attenuation of ambient noise in acoustically challenging situations, such as typical school classrooms can: i) facilitate the processing of sound and in particular speech stimuli by children with APD due to the improved signal-to-noise ratio (SNR) and ii) that the long-term use of such devices may lead to long lasting improvements of listening abilities in APD patients because the improved SNR may facilitate the emergence of new attentional and/or processing strategies that were in worst
SNR situations not achievable by these patients. Results form a first reported study show that children with APD can significantly benefit from the use of FM systems to improve their speech-in-noise comprehension abilities. We also report results from a second study that could evidence long term benefits of the FM treatment on subjective measures, psychoacoustic tests, as well as evidence for improved neural maturation in the auditory pathway as demonstrated by the maturation of auditory event related potential markers over a one-year period. All these results are discussed in the context of current consensus on APD diagnosis and management.

Keywords
Auditory Processing Disorders; APD; ADHD; Learning Disabilities; APD Management; FM systems; EduLink; Classroom noise

Introduction
Auditory Processing Disorder (APD) is a condition in which patients are experiencing important listening difficulties in the absence of clearly identifiable peripheral auditory deficit. Therefore, patients with APD typically have normal pure tone thresholds but experience difficulties in various auditory tasks including: sound localization and lateralization; auditory discrimination; auditory pattern recognition; temporal aspects of audition, including temporal integration, temporal discrimination (e.g., temporal gap detection), temporal ordering, and temporal masking; auditory performance in competing acoustic signals (including dichotic listening); and auditory performance with degraded acoustic signals (American Speech-Language-Hearing Association Consensus Committee, ASHA, 1995; 2005). Current consensus on APD management suggests the multidisciplinary involvement of therapeutic approaches...
including: 1. Direct therapeutic remediation; 2. Environmental modifications and 3. Compensatory strategies. The goal of the present article is to review recent advances and experimental results on the management of APD with environmental modifications with a particular stress on the usage of personal FM systems. The current review will therefore focus on point 2., for a detailed presentation on current definitions, known etiologies, diagnosis methods and other management approaches, readers are referred to Mülder, Rogiers & Hoen, (2007, the 6th–7th volume of Speech and Hearing Review), or Moore (2006). Environmental modifications are designed to improve acoustic clarity and enhance learning-listening (Bellis, 2002; 2003). It is universally accepted that all listeners perform better in an environment with acoustic clarity and desirable signal-to-noise ratio (SNR). Primary school children are particularly vulnerable to noise (Shield & Dockrell, 2003) and will experience high levels of noise in classrooms (Blake & Busby, 1994). It was also shown that children will not develop adult-equivalent resistance to noise and reverberation before late teenage years. Before this will be achieved, the younger the children, the more important the difficulties regarding listening in noise and/or in reverberant environments (Stelmachowicz, Hoover, Lewis, Kortekaas & Pittman, 2000; Jamieson, Kranjc, Yu & Hodgertts, 2004). In their review, Picard & Bradley (2001) have estimated that classrooms presented average noise levels of 4 to 37 dB A above the recommended levels and proposed ambient noises guidelines of 40 dB A maximal for 12 years old and older children and reverberation times of 0.5 s. According to these authors, younger students with normal hearing and listening faculties would require levels ranging from 39 dB A (10 – 11 years) to only 28.5 dB A (6 - 7 years old). Finally they suggested that children with suspected delayed speech processing in noise, such as APD children,
would require noise levels as low as 21.5 dB A at age 6 - 7 (see also Finitzo-Hieber, 1988; Fallon, Trehub & Schneider, 2000; Shield & Dockrell, 2004). If ambient noise levels in public rooms constitute an important challenge for normal hearing children or children with normal speech development, it gets almost impossible to overcome for children with auditory deficits of peripheral or central cause. Managing classroom acoustics plus the use of a personal FM system, both a part of managing the listening environment, should for these children be approached in a systematic matter. The use of FM systems has proven to be an extremely efficient mean of canceling surrounding noise in classrooms for children of various age and with various degrees and configurations of sensorineural hearing loss (Hawkins, 1984; Nabelek, Donahue & Letowski, 1986; Boothroyd & Iglehart, 1998; Anderson & Goldstein, 2004); unilateral hearing loss (Kenworthy, Klee & Tharpe, 1990), multiple sclerosis (Lewis et al., 2006), as well as cochlear implant users (Iglehart, 2004; Schafer & Thibodeau, 2004). The benefits provided by FM systems were estimated to be of approximately +15 dB SNR (Hawkins, 1984) and FM systems have often proven to be much more efficient in aversive conditions than other – even digital – noise canceling systems or directional microphones, at least in adults (Lewis, Crandell, Valente & Horn, 2004), or when the limits of amplification have been reached (e.g. McArdle, Abrams & Chisolm, 2005). Up to now however data on the management of children with APD with FM systems are still rare. Despite the current lack of large scale evidence, the management of APD children using FM systems is a generally admitted process. In this context, Rosenberg (2002) suggests a four-step management process:

1. Evaluating the student’s auditory processing strengths and weaknesses, determining the primary APD profile, and identifying APD profile...
indicators that support or contraindicate the use of a personal FM system;

2. Evaluating the acoustical classroom environment and recommending appropriate modifications;

3. Selecting and fitting the personal FM system that most appropriately meets the student’s needs;

4. Ensuring that the student and teacher receive in-service training and that efficacy measures are taken.

Perhaps one of the most important components of any APD management program is that of teaching children to become active rather than passive listeners (Bellis, 2003). As described by the same author, compensatory strategies training is not designed to remediate the underlying disorder, but rather to strengthen higher-order top-down skills. The more difficult task of auditory processing can then be given greater effort. It will also render any bottom-up remediation activities more effective by enhancing children’s active participation in such activities. Finally, teaching children compensatory strategies will also help them to live with the residual effects of their disorders, and to succeed in spite of them. Compensatory strategies training will include the strengthening of active listening techniques, and linguistic, metalinguistic and metacognitive abilities. Strengthening metacognitive and metalinguistic skills enables the child to recognize conditions that interfere with learning. They also allow the use of executive control strategies and linguistic resources, enabling the child to improve listening outcomes for his- or herself (Chermak & Musiek, 1997).

Finally, it is important that the audiologist and other professionals working with the child and parents help them understand the nature of the child’s auditory processing difficulty. This helps the child and parents to comprehend
how these difficulties impact learning and academic performance. The role of the audiologist in the comprehensive and multidisciplinary assessment and management of APD is described as follows by the Recommended Professional Practices for Educational Audiologists (EAA, 1997):

1. Evaluation and/or interpretation of auditory processing test results and educational relevance;
2. Communication with members of the multidisciplinary team;
3. Monitoring of the classroom environment;
4. Management of FM-equipment;
5. Counseling of parents and teachers on APD and the consequences, on strategies and modifications.

During the last years, numerous studies were dedicated to evaluating the benefits of personal FM systems use, to favor SNR improvements for children with APD in classrooms situations. The goal of the present article is to review research done on FM systems and recent advances in the domain of APD management with those assistive devices.

**Recent Studies on APD management and FM systems**

**Study I: Effect on understanding speech in classroom situations with the EduLink device**

Children with APD have pronounced difficulties in understanding speech in noisy environments as classrooms. The most effective way to improve the SNR in the classroom is the use of FM systems. The teacher’s voice is picked up and radio transmitted to a receiver worn by the student. The EduLink FM receiver...
is specifically developed to meet the needs of children with APD. The voice of the teacher is directly transmitted into the ear of the child. The ear canal remains completely open. Thus, environmental sound can be heard unaltered, and the child does not feel acoustically “isolated”. Only the teacher’s voice is amplified, which results in a SNR improvement. Interfering noise in a classroom not only consists of rustling papers or noise from heating and ventilation systems, but also of talking classmates. This is called informational masking, as there is not only a masking effect from the spectrotemporal energy of ambient noise, but also additional masking effects due to distraction of concentration and the linguistic information contained in concurrent speech signals. In order to verify the real-life advantages of using personal FM systems, a first study was conducted at the University Hospital in Zurich, Switzerland, to examine the effects of informational masking on speech understanding in children with APD as well as age matched control children and whether there was a benefit of using EduLink in conditions reflecting the situation in typical classrooms.

**Participants**

A total of 20 children entered this first study, 9 children with APD (5m, 4f, test group); diagnosed by local ENT doctors according to local standards and 11 children without APD (5m, 6f, control group). The age of included children ranged from 8-10 years and was balanced across groups (mean: 9 years and 2 months). It was confirmed that none of the children had additional attention deficit or hyperactivity. None of the children had a peripheral hearing loss (pure tone thresholds not exceeding 20 dB nHL in the 125 to 8k Hz range). The intelligence of all children was at least average (non verbal IQ scores > 90). All participants and their parents gave informed consent before entering the study.
**Materials and Methods**

Speech comprehension in noise was evaluated using the adaptive, German language, Oldenburg Sentence Test which is suited for children in this age group. This test measures the speech reception threshold (SRT), corresponding to the signal to noise ratio at which a 50% intelligibility score is reached. Test stimuli consisted in short five-item sentences (*Mary has three red books*, for example). The task for children was to repeat the sentences they could hear. Prior to testing it was ensured that all children were able to memorize five words in a row. In the present study, the test was conducted with or without EduLink and with two different types of competing noise: i) a stationary broadband noise, having the same power spectrum as the speech material of the test but not containing any linguistic information and ii) a female and a male talker each reading a story which was interesting for children. These two conditions will be hereinafter referred to as the speech-in-noise and speech-in-speech conditions respectively. Target sentences were presented from the front direction at a distance of 3 m of the participating children (Westra loudspeaker, type LAB-1001™). Noise was presented from both sides, at 90° and 270° and at a distance of 1 m (Genelec active loudspeaker, model 1029A™). In the speech-in-speech condition, the female talker was presented from the left loudspeaker, and the male talker from the right one. In both conditions, the noise level was kept constant at 60 dB A. The level of the target signal was constantly adapted depending on the intelligibility score obtained at each preceding trial until it stabilized at the SRT according to a standardized method (see Wagener & Brand, 2005 or Wagener, Brand & Kollmeier, 1999a and 1999b, for methodological details). After a short training period familiarizing children with the test setup, 20 to 30 test trials were usually needed before the SRT
could be obtained; the global speech test duration was of 15 to 20 min. In the with EduLink situation, personal FM devices were worn binaurally. The FM microphone (Phonak Communications, model Mini-Boom™) and transmitter (Phonak Communications, model Campus-S™) were installed close to the front loudspeaker in order to reproduce the condition of a seating teacher that would speak into the microphone, as would be the case in a typical classroom situation.

**Statistical Analysis**

Statistical significance of measured differences was assessed via repeated-measures analysis of variance (ANOVA) (alpha=.05) performed under STATISTICA 7.1 (©Statsoft Inc., 1984-2005) and considering individual measured SRT as dependent variables and including as 2-levels within-subjects factors: Group: (APD vs. Control Group), EduLink: (With vs. Without) and Noise: (Broadband vs. Speech). Whenever appropriate, post-hoc tests were performed using the LSD test or post-hoc comparisons adjusted for multiple comparisons via Bonferroni correction, both at alpha=.05.

**Results**

Figure 1 shows the results obtained by children from the two groups at the speech comprehension test in the speech-in-noise condition. This figure shows the SRT achieved by children form the APD and Control group, without the EduLink and with the EduLink. The lowest the SRT, the better or easier speech comprehension was. Average SRT measured without EduLink were of -5.1 dB (N=9, SD = 3.5) in the APD group and -7.1 dB (N=11, SD = 1.4) in the control group. When measured again with binaural EduLink assistance, scores reached -21.4 dB (SD = 7.0) in the APD group and -24.1 dB (SD = 3.0) in the control
group. EduLink therefore provided an advantage in broadband noise of -16.3 dB (SD = 4.8) to children with APD and -17.0 dB (SD = 1.4) to children in the control group.

![Figure 1: Speech understanding against a broadband speech modulated noise without EduLink and with EduLink.](Fig. 1)

Fig. 2 shows the results obtained in the speech-in-speech condition. Average SRT measured without EduLink were of +1.0 dB (SD = 4.8) in the APD group and -1.5 dB (SD = 2.2) in the control group. With EduLink, SRT improved to -17.3 dB (SD = 5.6) in the APD group and -17.3 dB (SD = 3.5) in the control group. EduLink therefore provided an advantage in concurrent speech of -18.3 dB (SD = 4.1) to children in the APD group and -15.8 dB (SD = 4.5) to children in the control group. Statistical analysis showed a significant main effect of Noise Type: (F(1, 8) = 45.5, p < .005) confirming that children were globally more annoyed by concurrent speech (average SRT in speech = -8.8 dB, SD = 9.5) than by a stationary broadband noise (-14.5 dB, SD = 9.4), the effect...
of informational masking in this case being evaluated to a disadvantage of approximately 6 dB (SRT). The effect of EduLink was also significant (F(1, 8) = 368.2, p < .001), average SRT without EduLink being of (-3.3 dB, SD = 4.4) and (-20.1 dB, SD = 5.6) with the EduLink. Thus the improvement provided by binaural EduLink fitting can be estimated to approximately 17 dB (SRT).

The second level interaction between those factors remained non significant (F(1, 8) = 0.02, n.s.), suggesting that the EduLink benefit was approximately equivalent in both noise conditions. The effect of Group was non-significant (F(1, 8) = 0.7, p = 0.4), APD and control children having produced similar SRT in this test. Furthermore, the Group effect did not interact neither with the type of noise (F(1, 8) = 3.7, p = 0.1), nor with the EduLink factor (F(1, 8) = 0.8, p = 0.4). This latter observation confirmed that APD and Control children were similarly annoyed by the different noise types and that the benefit of EduLink
was similar in the two children’s groups. Finally, the third level interaction also remained non significant (F(1, 8) = 2.9, n.s.).

**Study I: Discussion and Conclusions**

The goal of this first study was essentially to demonstrate and quantify the SNR advantage provided by personal FM systems in the presence of different types of interfering noise in a real-life, classroom like situation. A secondary goal was to evaluate the potential benefit of this type of devices for children with APD.

A first observation was that the conversational nature of concurrent speech mimicking the effect of speaking nearby classmates at a distance of 1 m to the listener created a significant drop of speech comprehension abilities compared to a situation where the noise was a stationary broadband noise. The magnitude of the supplementary informational masking could be estimated at 6 dB (SRT) in this particular situation and for this particular task. The fact that this observation was true both with and without the EduLink confirms that this type of assistive devices, using an open fitting design allows direct sound input and leaves this additional informational masking possible. Actually, this is of first importance as in classrooms situations, classmates can generate noise, but also very important and useful information when they talk together or respond to their teachers’ questions or when working in group discussion settings. All this constitutes crucial information that has to be kept even when using an FM system that should facilitate intelligibility of the teacher but also keep social interactions between children possible and as natural as possible as they participate in the development of normal social communicative skills (Pittman, Lewis, Hoover & Stelmachowicz, 1999). Children from both groups experienced comparable amount of annoyance due to the speech nature of the
second noise used. However, APD and Control children showed a marginally significant difference in the speech in speech condition (LSD test p = 0.04) that did however not survive the Bonferroni correction for multiple comparisons, certainly due to the small size of the tested populations (N = 9 and 11). Therefore, we have observed a strong tendency for children in the APD group to be more annoyed in the speech-in-speech condition than children in the control group that disappeared when these children used the EduLink (LSD test = 0.7, n.s). In the speech in speech condition (which is the condition reflecting typical classroom situations) children with APD reached the same speech understanding as the control group when using the EduLink. However, these observations would need to be confirmed by reproducing this experiment on larger test groups. With EduLink, speech understanding increased considerably in both groups, with an average EduLink SRT advantage of 17 dB (SRT) and no difference between groups reflecting the fact that APD children benefited form the SRT increase as much as control children. This observation is in agreement with former measures having estimated the benefit of FM systems to 15 dB (SNR) (Hawkins, 1984) and ensures that a sufficiently favorable signal-to-noise level is present at the children’s ears, which in turn allows for adequate speech understanding even in challenging acoustic environments.

In summary, children with APD often have more difficulties in understanding speech in noisy environments compared to normal hearing peers. In classrooms, there can be extensive background noise which is mainly from classmates talking. EduLink allows for substantial speech understanding improvements in such difficult environments. This ensures that the teacher can be heard well, which constitutes a prerequisite for effective learning. Therefore, in addition to conventional therapy, an FM system such as EduLink can be highly beneficial
for children with APD. Moreover, the long term use of EduLink might improve
the way APD children cope with the classroom situation and even improve
their ability to listen. APD children, when using the EduLink, might learn to
listen. This second assumption had to be verified a little further. Therefore, a
second study was run, in order to evaluate and quantify the long term benefits
of EduLink use by APD children. The mentioned results of this long term
benefits study were firstly published as an independent study in Friederichs &
Friederichs (2005), we will here only report main observations from this study
originally conducted at the private clinic of Dr. E. Friederichs In Heiligenstadt,
Germany.

**Study II: Ear-level FM receiver stimulates auditory neural
plasticity in children with APD**

Former studies could demonstrate that the everyday use of a personal ear-
level frequency-modulated (FM) device such as EduLink could significantly
help children with APD overcome their difficulties listening in noisy
environments such as classrooms (see Study I above and Crandell, Charlton,
Kinder & Kreisman, 2001). However, open questions remained as far as to
determine whether the use of EduLink could promote long term effects
observable with multiple testing procedures including subjective and objective
psychoacoustic testing. Another open issue was to evaluate the potential of
EduLink use to trigger neurophysiological plasticity mechanisms associated
with long term improved sound processing in children with APD. Subjective
as well as objective measurements can be obtained using questionnaires and a
variety of psychoacoustic tasks, following the evolution of scores over time. It
is also possible to study the cortical representation of sounds and their evolution in one individual by recording Auditory Event-Related Potentials (AERPs). This technique, derived from electroencephalography (EEG) evaluates cortical processing of sound via the measurement of brain waves associated with auditory perception. In AERPs, cortical processes show up as a succession of peaks of positive (P) or negative (N) potentials. Using the recording of AERPs, different studies could identify clear modifications of cortical sound processing in children with attentional deficits (Schochat, Scheuer and Andrade, 2002) and recent studies could even show that children with Specific Language Impairment (SLI) had brain processing of sound stimuli revealing auditory attentional impairment (Stevens, Sanders and Neville, 2006). Similar results were also observed in children with reading disorders (Sharma et al., 2006). These results suggest once again the existence of an important auditory processing deficit compound in the impairment of children diagnosed as SLI or dyslexic. Amongst the different evoked components that can be studied in late evoked auditory potentials, the N1 and P2 are classical central auditory evoked components (e.g. Rugg and Coles, 1995). N1 and P2 waves typically reflect early cortical acoustic processing levels and are modulated by the amount of energy engaged in the processing of a particular stimulus. Typically, the N1/P2 complex of waves is reduced in patients suffering from sensory- or attentional- processing deficits (see Barry, Johnstone, & Clarke (2003) for review, or Brown et al., 2005 for recent data on attention disorders). Using various electrophysiological measurements, including AERPs but also Auditory Brainstem Responses (ABRs), different authors could evidence neural plasticity mechanisms caused by auditory training in: learning impaired children (Warrier, Johnson, Hayes, Nicol & Kraus, 2004) or dyslexic children (Santos, Joly-Pottuz, Moreno,
Habib & Besson, 2006). The goal of the present study was to assess subjective, objective and most importantly, electrophysiological long term outcomes of EduLink use in children with APD.

Participants

20 children aged 7 to 14 (mean = 10.2 years, SD = 1.9) entered this study that was conducted over a one-year period. All children were normal hearing (pure tone thresholds > 20dB HL in the 250 Hz to 8 kHz range) and normal cognitive abilities (IQ>90). All test subjects had a personal history of learning difficulties and auditory difficulties consistent with APD and attention related concerns. 8 children were diagnosed as having Attentional Disorders / Hyperactivity Disorders (ADHD), according to DSM-IV criteria and were treated accordingly. In this study ADHD syndromes were considered as being a comorbid condition of APD. Parents and children gave informed consent before entering the study. Children in the FM test group (n = 10) used an ear-level FM receiver (EduLink technology in a BTE housing) at least 5 hours a day, 5 days a week, during school hours. The control group (n = 10), was constituted of 10 ADHD / APD children that during the same period did not wear any type of auditory assistive device but received, as all children included the usual ADHD intervention program.

Materials and Methods

Different subjective, objective and electrophysiological measures were conducted at the beginning, 6 months and 1 year after the start of daily FM use.

Subjective testing consisted of questionnaires given to the children’s parents
and teachers, evaluating the impact of FM use on social-behavioral factors as subjective attentional, focusing abilities, scholar outcomes or precise scholar tasks as dictation.

**Objective behavioral measures were obtained from 5 psychoacoustic tests including:**

- Measurement of discrimination thresholds for: i) intensity, ii) frequency and iii) temporal gap in broadband noise,
- iv) Temporal order judgment for monaural stimulation,
- v) Side order judgment for binaural stimulation.

All discrimination tests were based on two alternative forced-choice procedures as described in Schäffler, Sonntag, Hartnegg & Fischer, (2004) and Fischer & Hartnegg (2004). The two stimuli delivered in each test were:

  i) Intensity discrimination: white noise, 300 ms duration, ISI = 150 ms, Reference signal at 55 dB HL.

  ii) Frequency discrimination: reference tone 1 kHz, 300 ms duration at 63 dB HL.

  iii) Temporal gap detection: 60 dB HL, 300 ms white noise tones one continuous, one with a gap, ISI = 300ms.

  iv) Temporal order judgment: 1 and 1.12 kHz tones presented randomly, duration of 200 ms, at 63 dB HL. Children must indicate the tone sequence.

  v) Side order judgment: clicks at 55 dB HL one in the right ear, the other in the left ear randomly. Children must indicate which ear was stimulated first, ISI = 300 ms at first trial and then decreased progressively.

Finally, AERPs were derived from an EEG recording done with a 26 –
electrode cap. In order to maximize the N1 and P2 amplitudes, only posterior electrodes (Pz, P3 and P4) were taken into account in this experiment. During the recording, electrodes were referenced to the left earlobe. Vertical electrooculography (EOG) acquired on two electrodes was used to monitor eye blinks. Data were acquired using a 32-channel amplifier (Brainamps™) with an acquisition band of 0.5 to 30 Hz and an analogue to digital (A/D) sampling rate of 1 kHz. EEG was continuously acquired while children were taking part in a standard oddball paradigm in which frequent auditory stimuli (2.2 kHz tones, 2/3 of trials) and infrequent stimuli (4 kHz tones, 1/3 of trials) were presented, the task for children was to recognize the infrequent stimuli and push a response button each time they did. This ensured for attentional focusing and accurate processing of the auditory stimuli. Each stimulus had duration of 50 ms and the ISI was 3025 ms. Recording sessions consisted of 100 randomly distributed auditory stimulations.

All tests were performed without the EduLink being worn in order to evaluate the long term benefits provided by the usage of the assistive device and not the immediate SNR improvement.

Data Analyses

Statistical analysis of questionnaires data and psychoacoustic tests were done using paired t-tests. Electrophysiological data were first segmented in 800 ms long samples starting at tone onset, for frequent and infrequent stimuli. In this paper we will only report results obtained for infrequent tones that were correctly identified by children. Samples containing eye movements or artifacts exceeding +/- 140 microvolts deviations from baseline were automatically
excluded using the BrainVision analysis software and surviving samples were averaged together as Grand Average waveforms. Finally, individual recordings were averaged together for group data visualization of the AERPs. Statistical analyzes were performed on averaged scalp potential values on the N1 and P2 component, defined as the first positive deviation following the N1 component, in the 130 to 290 time window. Statistical significance of observed differences was evaluated using a temporal sample by sample rolling t-test under the software Brain Analyzer. All analyzes were performed at an alpha = .05 level of significance. In the current review, we will just report main results of this study, for a detailed report, readers are referred to the Friederichs & Friederichs (2005) original paper.

**Results: Subjective social behavioral evaluation**

Figures 3 and 4 show parents’ and teachers’ subjective judgments of their child’s social behavior averaged over six visits performed in 1 year. Subjective improvements were very significant. Parent’s of APD children judged that thanks to the use of EduLink, their children better understood teachers in 94 % of cases and teachers thought they were better understood in 100 % of the cases. Parents and teachers thought the EduLink was improving the ability of children to focus on details at 86 % and 82 % respectively. Finally, dictation came easier to children for 70 % of the parents and 67 % of the teachers.

Altogether, these observations highlight the benefit of daily FM use for children with APD and subjective social behavioral improvements. For both parents and teachers, children wearing the EduLink experienced notable and constant subjective benefits.
Objective psycho-acoustical evaluation

From the 5 originally conducted psychoacoustic tests 2, namely frequency discrimination and side order judgment, showed significant and constant improvement for children in the EduLink group compared to children in the
control group (Fig. 5). Paired t-test (p<.05 at third visit, at second visit n.s). None of the three other tests did show any significant change. It is interesting to note that these two tests reflect typical primary difficulties people with hearing loss encounter, decreased frequency- and binaural temporal- resolutions.

Fig. 5: Percentage of correct responses given to two behavioral tests: side order judgment (upper) and frequency discrimination (lower) for children in the APD group (thick lines) and control group (dotted lines).

Electrophysiological measures (AERPs)

Electrophysiological results showed a clear positive outcome of daily FM use in children with APD: it appears to stimulate central neural plasticity. Figure 6 shows the AERPs obtained for the three test electrodes for the detection of infrequent tones by children in the EduLink and control groups, before, after 6 months and after 1 year. At the beginning of the study children from both groups showed classical anomalies of the N1/P2 complex, the different waves being hardly recognizable. In the FM group, the maturation of the N1/P2
complex over time is very impressive; in particular, during the year of FM use, in participating children the amplitude of the P2 AERP component increased constantly, which was not the case for children in the control group. This maturation of the cortical response is likely to be due to the better auditory stimulation obtained by the use of an ear-level FM receiver, which would help the acquisition of more stable and stronger cortical representations of sounds.

![AERP recordings obtained before, after 6 months and after 1 year in EduLink and control children.](image)

**Study II: Discussion and Conclusions**

In addition to good acceptance and positive subjective outcomes of personal FM device use, this study demonstrates that long-term use of such instruments
by children with APD may lead to facilitated central neurophysiological plasticity. This phenomenon is reflected in parallel behavioral improvements. These very encouraging observations may give professionals and users hope for real and profound improvements of hearing capacities via the use of an ear-level FM receiver like EduLink.

**General Discussion and Conclusion**

Multiple studies have revealed that noise affects learning for all children, even more so for children with specific deficits due to Auditory Processing Disorders (APD), Attention Deficit/Hyperactivity Disorders (ADHD), Specific Language Impairment (SLI), specific Learning Disabilities (LD) and so on. Coping with degraded, reduced, or distorted speech is fatiguing, so the children have a natural tendency to tune out, get distracted, and misbehave.

An Auditory Processing Disorder is a pathological condition in which symptoms of hearing loss appear in children that have normal auditory thresholds. This is because the nature of the problem is to be found outside of the hearing organ. The difficulties these children experience find their roots somewhere in the long and highly complex processing chain that binds acoustical information detection and amplification at the cochlear level to the higher-order processing skills analyzing auditory information and specific linguistic and metalinguistic processes leading to speech comprehension. The resulting impairments have dramatic implications for these children because they hinder their ability to process speech appropriately which burdens their general learning abilities. Although today the exact neurogenesis or neurological causes of APD are still unknown, the global picture of how to diagnose and treat APD has become
clearer over the last years. In this context, it is clear that management should be multidisciplinary and consider the help of FM devices as an efficient manner to provide children with better acoustic cues in order for them to train bottom-up processing and develop and reinforce their top-down linguistic skills.

EduLink allows for substantial speech understanding improvements in such difficult environments. This ensures that the teacher can be heard well which is the prerequisite for effective learning. Behavioral improvements have been found in children using EduLink. Long-term use of such instruments by children with APD may lead also to facilitated central neurophysiological plasticity.

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