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By Hanne Pernille Andersen, PhD

EVIDENCE FOR THE **EFFECTIVENESS** OF THE AUDIBILITY EXTENDER IN **RESTORING THE PERCEPTION OF HIGH-FREQUENCY SOUND**

Introduction

For many hearing aid users, the primary motivation for wearing hearing aids is to improve speech perception. However, for people with severe or profound hearing loss, it is often not possible to restore high-frequency hearing by means of conventional amplification. This has been attributed to dead regions in the cochlea with no functioning inner hair cells (Moore, 2001) and limitations of the hearing aid in the form of insufficient maximum gain, the occurrence of feedback before the necessary amplification level is reached, and reduced output due to the use of thin-tube open-mould fittings (Kuk, 2007). Whatever the reason(s), limited access to high-frequency cues is critical, as this can have a detrimental effect on both speech perception and the perception of environmental sounds, such as an alarm or birdsong.

Plosive and fricative consonants, such as /s, ʃ, f, t/, are particularly difficult to perceive for people with high-frequency hearing loss (Elfenbein et al., 1994; Flynn et al., 1998). This means that the ability to discriminate minimal noun pairs (e.g., 'see', 'she', 'free', 'tree') and grammatical markers, such as verb tense and singular vs. plural (e.g., 'sit', 'sits'; 'cat', 'cats') will be impaired in children and adults with high-frequency hearing loss.

Furthermore, limited access to high-frequency speech sounds has been found to result in a delay or failure of normal language development in hearing-impaired children (Elfenbein, 1994; Stelmachowicz et al., 2004). This makes it highly relevant to explore the possibilities of new technologies to expand the range of audible sounds.

The inability of conventional amplification to secure audibility for people with severe or profound high-frequency hearing loss has led to the application of alternative strategies. One such strategy is the linear frequency transposition technique, used in the Audibility Extender feature in Widex hearing aids. With this technique, high-frequency information is shifted to a lower frequency region with some residual hearing. The Audibility Extender feature performs what is referred to as **linear** frequency transposition. This means that the feature preserves the harmonic structure and modulation ratio of the original signal. It is therefore equally capable of shifting both speech and environmental sound. To give an example, birdsong will still sound like birdsong, only at a lower pitch, when transposed by means of the Audibility Extender feature.

The ability of the Audibility Extender feature to improve speech perception and the subjective listening experience when listening to environmental sounds has been tested in a number of studies with hearing-impaired children and adults. The most important findings are summarised in the remainder of this Widex-Press as follows:

Speech perception and production
- Speech recognition and production in children with gradually or precipitously sloping hearing loss
- Speech recognition in adults with gradually or precipitously sloping high-frequency hearing loss
- Speech recognition in young people with profound hearing loss

Environmental sounds
- Subjective preferences of adults
- Subjective preferences of children

SPEECH PERCEPTION AND PRODUCTION

The efficacy of the Audibility Extender feature in improving speech perception and production in children and adults has been tested in a number of studies (Auriemmo et al., 2008; 2009; Smith et al., 2009; Gou et al., 2011; Kuk et al., 2007; 2009).

Speech recognition and production in children with gradually or precipitously sloping hearing loss

Notable improvements in speech perception and production were first reported in a case study involving two children with precipitously sloping high-frequency hearing loss (Auriemmo et al., 2008). One child was a 13-year-old girl, the other an 8-year-old boy. Both children were several years below age level in terms of language proficiency despite having received speech therapy. The children were fitted with Inteo-19 hearing aids with the Audibility Extender feature enabled. Their speech perception and production accuracy was tested with their own aids prior to the fitting, and after six weeks of use of test hearing aids with the Audibility Extender feature.

The girl's correct consonant identification scores increased from 28% at 30 dB HL and 56% at 50 dB HL with her own aids, to respectively 35% and 65% after a six-week trial period. Her production accuracy scores for /s/ and /z/ went from 79% on a reading task and 85% on a conversational task to 94% and 95%, respectively, at the end of the trial. Improvements in speech perception and production accuracy were also recorded for the boy. The improvement in production accuracy for /s/ and /z/ was quite dramatic. The boy's scores went from 41% on a reading task and 61% on a conversational task to 80% and 81%, respectively, after six weeks of use of the test hearing aids with the Audibility Extender feature. Both children also reported hearing environmental sounds, such as the telephone ringing, soda "fizzing", or water dripping, which they had never heard before.

Auriemmo et al. (2009) subsequently investigated the effect of the Audibility Extender feature on speech recognition and production in a larger group of school-aged children with high-frequency hearing loss. Ten children between the ages of 6 and 13 years with precipitously sloping sensorineural hearing loss participated in the study. All the children were oral communicators, and all were partially or fully emerged in mainstream education. Nine of the children were fitted with Widex Inteo-19 hearing aids with skeleton earmoulds for the experiment. One child was fitted with Widex Inteo-9 hearing aids. Auditory training sessions of approximately 30 minutes were conducted once a week by an audiologist with the test hearing aids in the default (Master) and the Audibility Extender programs. Phoneme recognition and accuracy of fricative articulation were tested in three conditions:

1. With the child's own hearing aids
2. With the Widex Inteo hearing aids in the Audibility Extender program (Linear Frequency Transposition 'On')
3. With the Widex Inteo hearing aids in the default (Master) program (Linear Frequency Transposition 'Off').

The children were tested at their initial fittings, and after three and six weeks of use. The tests were performed at soft (30 dB HL) and normal (50 dB HL) input levels. The results showed that the children performed significantly better on consonant recognition with the test hearing aids in the default program and in the Audibility Extender program than with their own hearing aids at both soft and normal input levels. Significant increases in correct consonant and vowel recognition scores were seen with the Audibility Extender feature after three and six weeks at soft input levels. Similar gradual improvements were seen at normal input levels, although the trend was statistically non-significant.

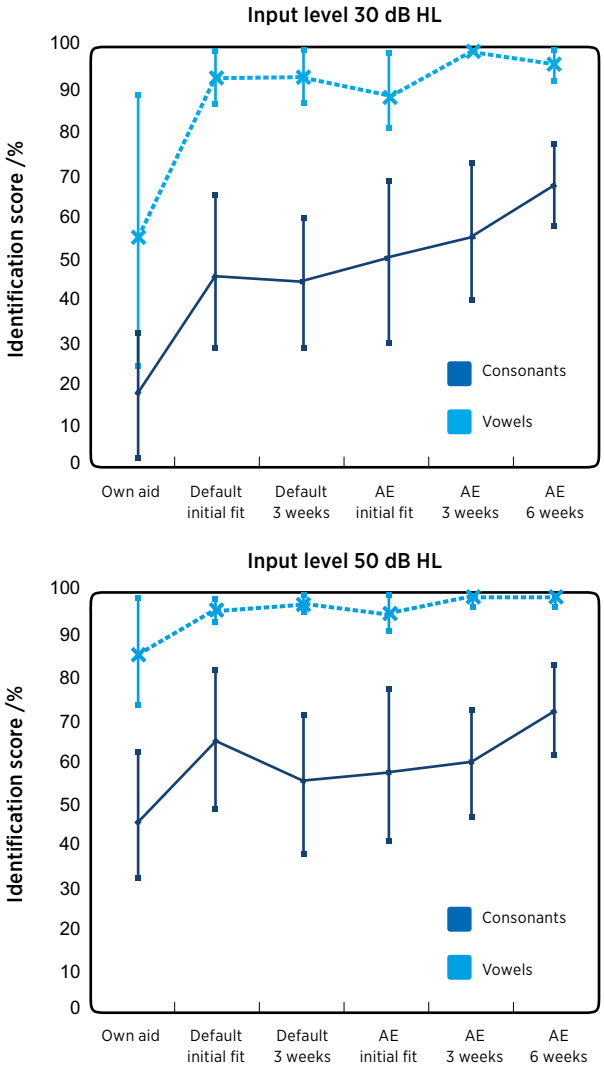

Figure 1. Consonant and vowel scores at input levels of 30 dB HL (top) and 50 dB HL (bottom) with the children's own aids, with the test hearing aids in the default program at the initial fitting and after three weeks, and with the test hearing aids in the Audibility Extender program at the initial fitting and after three and six weeks. Reproduced from Auriemmo et al., 2009.

The children's accuracy in producing /s/ and /z/ was also assessed using a reading task and a conversational task. The results are shown in Figure 2. Statistical tests revealed that the children's reading task performance was significantly poorer with their own hearing aids than with the test hearing aids in the Default program and in the Audibility Extender program. Furthermore, the children's performance was significantly better in the Audibility Extender program than in the Default program after six weeks. A similar, although non-significant, trend was seen with the conversational task.

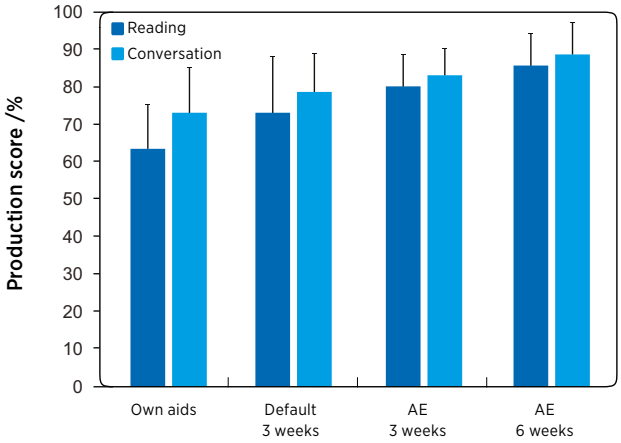

Figure 2. Production accuracy of /s/ and /z/ on a reading task (dark blue) and a conversational task (light blue) with the children's own hearing aids, the test hearing aids in the Default program after three weeks, and the test hearing aids in the Audibility Extender program after three and six weeks. Reproduced from Auriemmo et al., 2009.

Taken together, the results obtained by Auriemmo et al. (2008; 2009) indicate that the Audibility Extender feature is capable of generating improvements in both speech recognition and speech production in school-age children with precipitously sloping high-frequency hearing loss.

The long-term effect of the Audibility Extender has been investigated by Smith et al. (2009) over a period of six months. They examined the benefits of the Audibility Extender feature for a group of school-aged children with sloping high-frequency hearing loss. Six children between the ages of 9 and 14 participated in the study. All the children were oral communicators and attended mainstream schools. Three of the children were fitted with Widex Inteo-19 hearing aids, and three of the children were fitted with Inteo-9 hearing aids for the experiment. The Audibility Extender program was set up as the first program in the test hearing aids. The default (Master) program (without linear frequency transposition) was set up as the second program.

Speech perception abilities were measured using CNC word and phoneme tests with and without frequency transposition at six weekly intervals for six months (24 weeks). Testing was performed under both an audio-visual condition where the children had access to both auditory and lip-reading cues, and an audition-alone

condition where they only had access to auditory cues. Speech production accuracy was tested by means of a word and sentence production task at the end of the 24 week trial. Results for the audition alone presentation mode showed a general improvement for all participants 12 weeks after the fitting. This was sustained in four of the six participants after 24 weeks. Results for the audio-visual presentation mode showed more variability. According to the authors, this is probably because this mode is heavily influenced by the amount of lip-reading training received by the children prior to the study, and possibly also by their familiarity with the words used in the test.

Improvements in speech production, including improved fricative production and a reduction in slurred speech, were recorded for five of the six children after the 24 week trial. One child (Case 5) showed no difference in performance after the trial, despite the fact that her perception accuracy score improved in all conditions after 12 weeks, and in all but one condition after 24 weeks. The overall speech production results obtained by the six children at the beginning and end of the trial are shown in Table 1 below.

Table 1. Speech production scores (the Goldman-Fristoe 2 Test of Articulation) obtained by the six participants at the beginning and end of the 24 week trial. Reproduced from Smith et al., 2009.

Comparison of Goldman-Fristoe 2 standard scores

Standard scores	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
Pre-fit	54	74	74	90	78	87
Post-fit	90	98	104	100	78	95
Difference	+36	+24	+30	+10	0	+8

In summary, the results obtained by Smith et al. (2009) also suggest that linear frequency transposition, as incorporated into the Audibility Extender feature, can provide speech perception and speech production benefits for school-age children with high-frequency hearing loss.

Speech recognition in adults with gradually or precipitously sloping high-frequency hearing loss

As discussed above, the Audibility Extender feature has been found to have a positive impact on speech perception and production in children. The question is whether these results are generalisable to adults well past the critical period for language acquisition. This has been investigated by Kuk et al. (2007; 2009).

Kuk et al. (2007) set out to investigate whether linear frequency transposition could alleviate some of the limitations of thin-tube open-ear fittings. This type of hearing aid solution has become rather popular for cosmetic reasons and because they offer improvements in the user's perception of their own voice. However, this hearing aid solution also leads to a reduction in high-frequency output of 5-15 dB compared to regular-tube closed-ear solutions. Thus, unless users have a mild degree of hearing loss, they may not receive sufficient compensation in the higher frequencies using conventional amplification (Kuk et al., 2007). Frequency transposition is therefore an interesting alternative feature for candidates with a relatively severe degree of hearing loss in the high frequencies. The efficacy of the Audibility Extender feature in improving speech recognition for wearers of thin-tube, open-ear solutions was consequently tested in an experiment involving 13 adults with steeply sloping high-frequency hearing loss (Kuk et al., 2007). The participants trialled Widex Inteo open-ear élan hearing aids for a two-week period. The test hearing aids contained two listening programs: one with frequency transposition Off, and one with frequency transposition On. The participants were instructed to try both programs during the trial period. Consonant and vowel recognition was tested by means of nonsense syllables at presentation levels of 30 and 50 dB HL initially and after two weeks.

As shown in Figure 3, the participants' consonant recognition scores were better with the Audibility Extender feature activated already at the initial visit. This result remained after the two-week trial period. The greatest improvement observed (12%) was in the consonant score obtained with the Audibility Extender feature On at the softer presentation level (30 dB HL). As may be seen in Figure 4, the participants' vowels recognition scores were either slightly better or the same with the Audibility Extender feature On compared to in the Off condition. Thus, the results indicated that frequency transposition does not negatively affect vowel recognition; if anything it seems to have improved it slightly. The main findings of the study are displayed in Figures 3 and 4 on the next page.

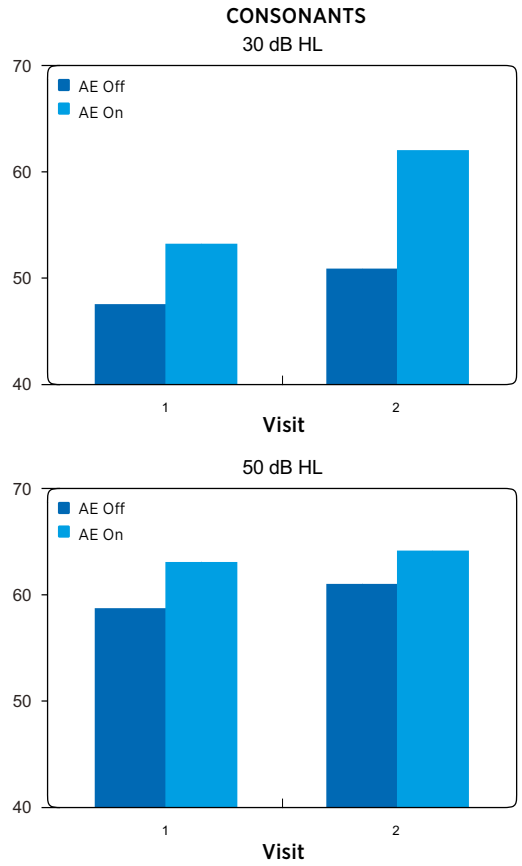

Figure 3. Average consonant identification scores at 30 dB HL (top) and 50 dB HL (bottom) initially and after a two-week trial. Reproduced from Kuk et al. (2007).

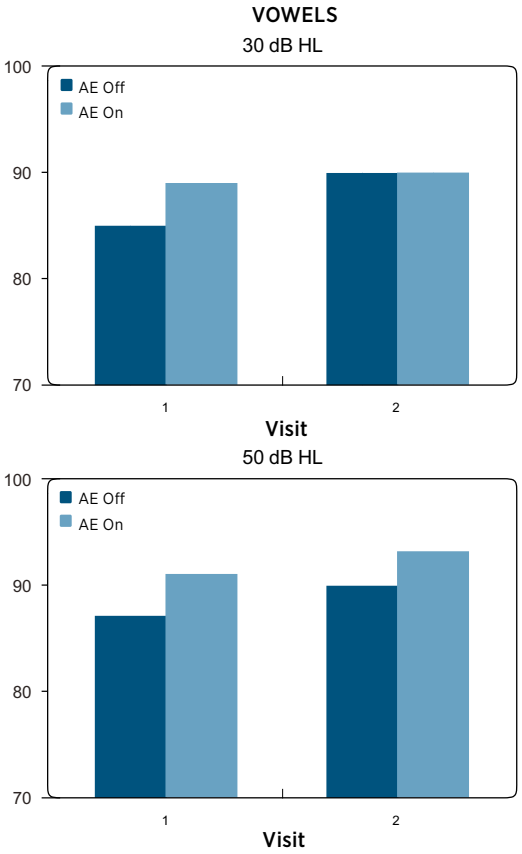

Figure 4. Average vowel identification scores at 30 dB HL (top) and 50 dB HL (bottom) initially and after a two-week trial. Reproduced from Kuk et al., 2007.

Consonant identification after a two-month trial period with the Audibility Extender program was examined by Kuk et al. (2009) in an experiment involving eight adults with severe-to-profound high-frequency hearing loss. Seven of the participants were fitted with Widex m4-*m* micro BTE hearing aids, while one was fitted with the m4-19 model, which is a power hearing aid. The Audibility Extender program was the only available listening program in the test hearing aids during the trial period. The participants wore the test hearing aids at home for one month and were instructed to carry out a PC-based training program of daily exercises involving a selection of voiceless stop and fricative consonants and vowels. The participants' consonant recognition ability was measured in quiet and with babble noise in the background using 32 nonsense syllables as stimuli. The stimuli were presented by a female speaker at 50 and 68 dB SPL. Consonant recognition was tested initially with and without frequency transposition, after one month of training, and after another month during which no training was required. A statistically significant improvement was found in the identification scores for fricatives, and a clear, but statistically non-significant improvement was observed in the participants' consonant recognition scores across consonant classes (stops, fricatives, affricates, approximants, and nasals) in both quiet and noise after the two-month trial period. The results obtained in babble noise are displayed in Figure 5 below.

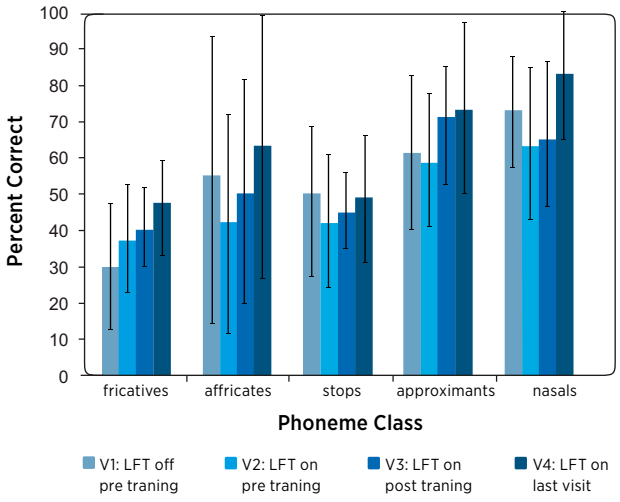

Figure 5. Consonant scores measured at 68 dB SPL in babble noise at the initial visit with and without frequency transposition activated (V1 +V2), and with frequency transposition activated after one month's (V3) and two months' (V4) use. Reproduced from Kuk et al., 2009.

Speech recognition in young people with profound hearing loss

Linear frequency transposition has been found to produce successful outcomes for children and adults with precipitously sloping high-frequency hearing loss

(Auriemmo et al., 2008;, 2009; Kuk et al. 2007; 2009; Smith et al., 2009). One very relevant question to ask is whether successful outcomes are also possible in hearing aid users with severe to profound hearing loss across the entire frequency range. This was investigated by Gou et al. (2011) in a study involving seven young people between the ages of 13 and 25 with severe to profound hearing loss. All the participants were oral communicators, and were integrated into mainstream education. The participants were divided into two sub-groups based on their audiometric configuration. One group (A) comprised four young people with pure tone thresholds of ≤ 100 dB at 1 kHz. The other group (B) had more profound hearing loss with pure tone thresholds of >100 dB at 1kHz. Thus, the first group was within the fitting range of the experimental aids (Widex mind440 m4-19 power model) except in the high frequencies where audibility would be provided by transposition. The second group's hearing losses exceeded the recommended fitting range, not only in the high frequencies where audibility would be achieved via transposition, but also in the low and mid-frequencies.

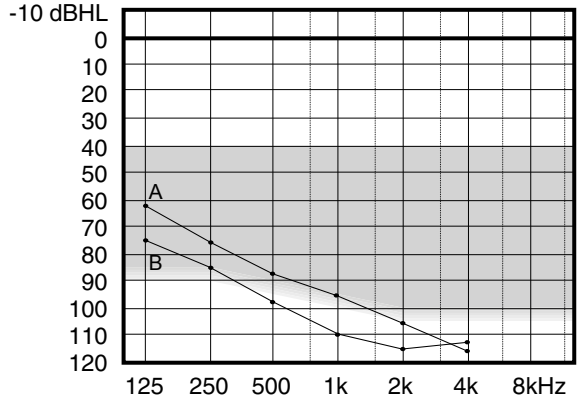

Figure 6. The recommended fitting range of the experimental aid (Widex mind440 m4-19). 'A' and 'B' refer to the average HTLs for the two groups of participants. Reproduced from Gou et al., 2011.

The Audibility Extender program was set up as the primary program. The default (Master) program without frequency transposition was included as the second program, but none of the participants reported having used it during the trial period.
Phoneme and word recognition was tested after 4, 8, and 12 weeks and compared with the results for the participants' own aids. In addition, unaided thresholds, thresholds with the participants' own hearing aids, and with the Audibility Extender program were also measured after four weeks of use. Notable improvements were observed in both aided thresholds while listening with frequency transposition and in speech perception. In group A, the total number of correct identifications went from 46% with the participants' own aids to 86% with the Audibility Extender program after 12 weeks of use. In the more profoundly impaired group (B), correct identifications increased from 39% with the participants' own aids to near-perfect identification of 94% with the Audibility Extender program. Group A also showed consistent improvement in all syllable and word identification tasks, while group B improved in four out of six tasks.

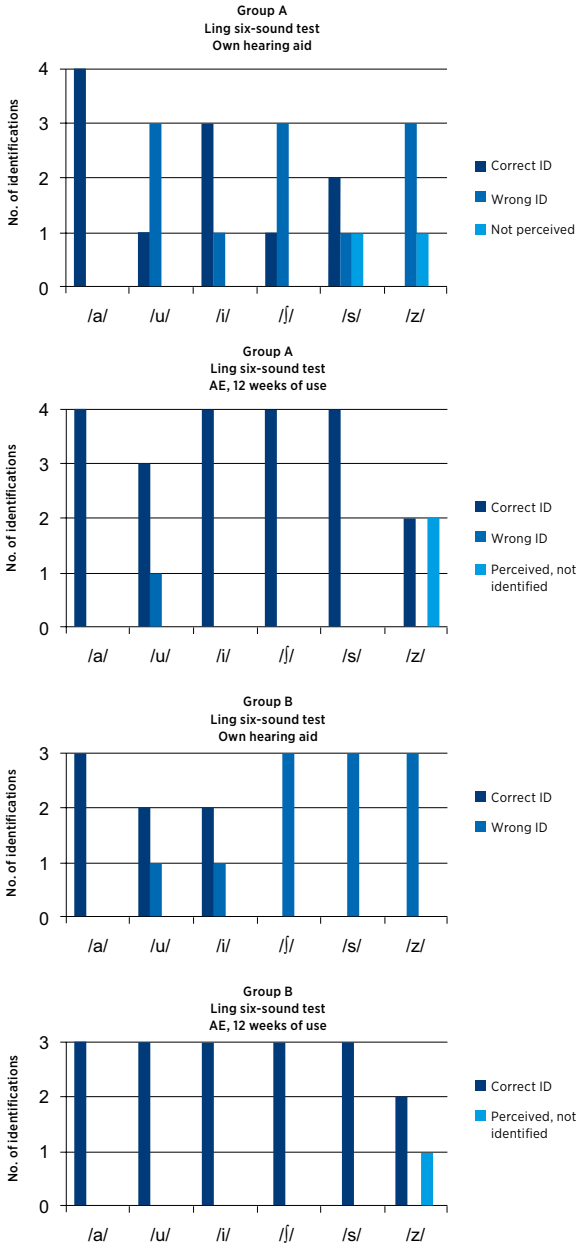

Figure 7. Correct and incorrect identifications of each phoneme with the participants' own hearing aids (upper panels) and with the Audibility Extender program after 12 weeks of use (lower panels). Reproduced from Gou et al., 2011.

Thus, the results obtained by Gou et al. (2011) suggest that positive outcomes are possible with the Audibility Extender feature for people with relatively little residual hearing in the frequency regions to which the signal is transposed.

ENVIRONMENTAL SOUNDS

As mentioned in the introduction, impaired speech perception is not the only negative consequence of high-frequency hearing loss. People with high-frequency hearing loss are often deprived of a range of environmental sounds, such as doorbells, birdsong, and the high-frequency components in music. Environmental sounds often contain harmonic sounds and may also be frequency and/or amplitude modulated. Since the linear frequency transposition technique applied in the Audibility Extender feature preserves the harmonic structure and modulation ratio of the original signal, this technique, should, at least in theory, be equally capable of shifting both speech sounds and environmental sound.

The efficacy of the Audibility Extender feature in reproducing environmental sounds in a manner which is pleasant and acceptable to the wearer has been investigated by Kuk et al. (2006; 2007) and Auriemmo et al. (2009).

Subjective preferences of adults

Initial subjective preference for listening with the Audibility Extender feature On vs. Off was investigated by Kuk et al. (2006) in a study of 16 people with varying degrees of high-frequency hearing loss. Five of the participants had a precipitously sloping high-frequency hearing loss and normal hearing below 1 kHz. The remaining 11 participants had a sloping moderate to severe high-frequency hearing loss. The participants were fitted with Widex Inteo élan, Inteo IN-9, or Inteo IN-X (ITC) models with the Audibility Extender feature included. Their subjective preferences for listening to environmental sounds with the Audibility Extender feature On vs. Off was tested by means of 12 bird songs, obtained from different species, and 12 musical passages.

As illustrated in Figure 8, considerable variation was observed in the participants' initial preferences. However, on average, they preferred to listen with the Audibility Extender feature On for over 60% of the bird songs.

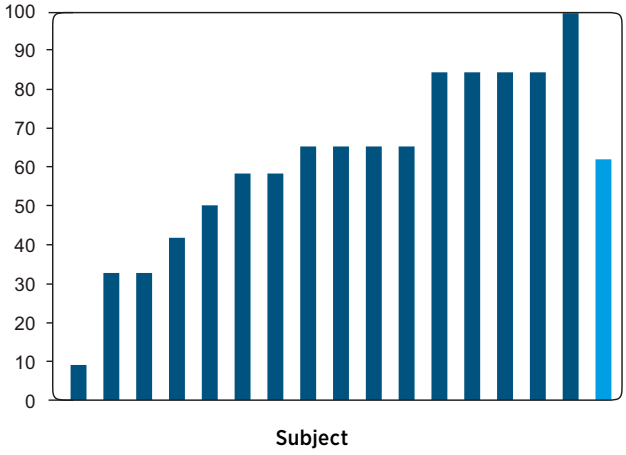

Figure 8. The participants' individual preference for the AE-On condition using bird songs as stimuli. The average preference is shown in light blue. Reproduced from Kuk et al., 2006.

Preferences also varied when music was used as stimuli (see Figure 9). However, on average, there was a preference for the AE-On condition 55% of the time.

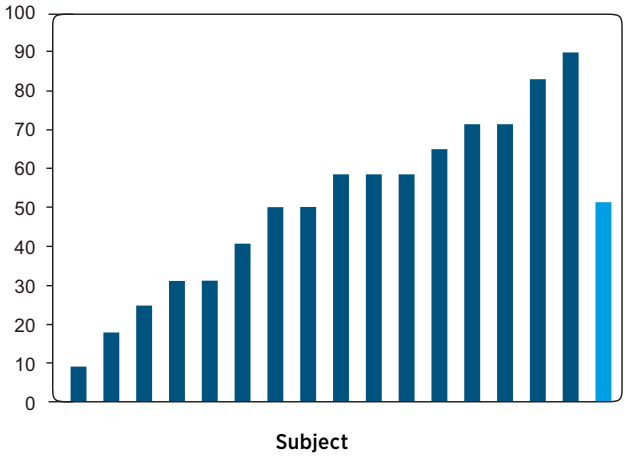

Figure 9. The participants' individual preference for the AE-On condition using music as stimuli. The average preference is shown in light blue. Reproduced from Kuk et al., 2006.

The authors point out that these preferences were obtained at the initial fitting without any acclimatization, and speculate that acceptance may increase as they gain more experience with transposed sounds.

Data on subjective preferences for listening to environmental sounds with linear frequency transposition activated after a period of acclimatisation have subsequently been reported by Kuk et al. (2007). The study also investigated speech recognition, and the study design has already been summarised in detail in the section on adult speech recognition above. Subjective preferences for listening to birdsong, music, and speech from a female speaker with the Audibility Extender feature On vs. Off were obtained from 13 hearing-impaired subjects after a two-week trial period. The results are summarised in Figure 10.

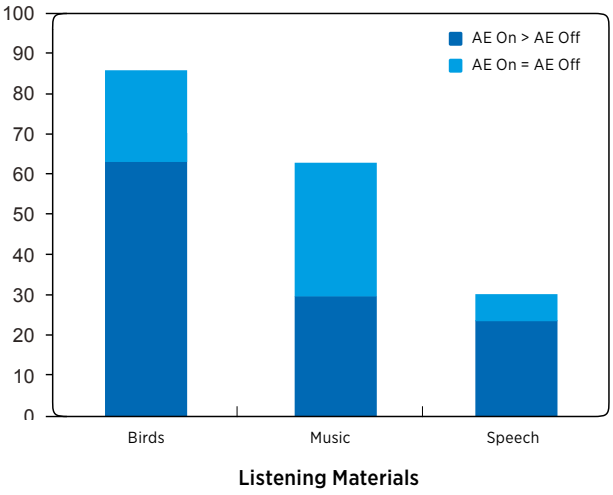

Figure 10. Preference for the AE-On condition vs. the AE-Off condition with three types of stimuli; birdsong, music, and female speech.

When birdsong was used as stimuli, more than 70% of the subjective preferences fell in the AE-On category. This decreased to approximately 65% when music was used, and to 30% when speech from a female speaker was used as stimuli. This decrease in subjective preference as a function of increased stimulus complexity is in line with what was observed in Kuk et al.'s (2006) initial investigation.

A comparison of the preferences obtained by Kuk et al. (2006) at the initial fitting with the results obtained after a two week trial period (Kuk et al., 2007) (60% vs. 70% for birdsong; 55% vs. 65% for music) indicates that acclimatisation may result in increased acceptance when listening to environmental sounds with frequency transposition.

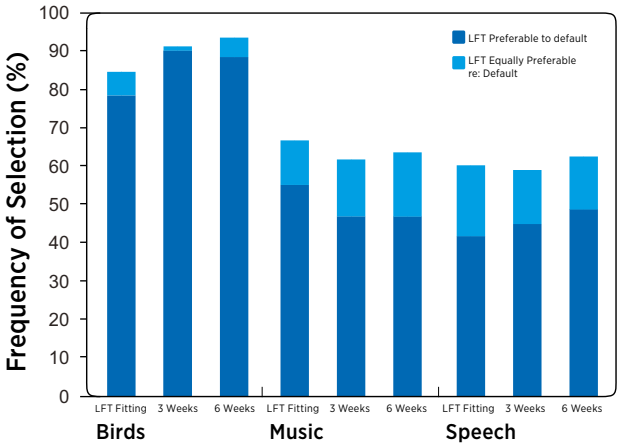

Figure 11. Preference for the Audibility Extender program when listening to birdsong, music and speech produced by a female speaker at the initial fit, and after three and six weeks of use. Reproduced from Auriemmo et al. (2009).

Subjective preferences of children

The study by Auriemmo et al. (2009) summarised in the section on children's speech perception and production also investigated the subjective preference of ten school-aged children for listening to environmental sounds with and without frequency transposition. The children's subjective preferences for listening to bird songs, music, and speech produced by a female speaker with the Audibility Extender program vs. the default (Master) program with no frequency transposition were measured at the initial fitting, and after a three-week and six-week trial period. The main findings are summarised in Figure 11. The height of the bars indicates the percentage of time the Audibility Extender program was more preferable or equally preferable to the default program.

It may be seen that almost 90% of the children preferred listening with the Audibility Extender program when the stimuli were bird songs. The preference was approximately 60% when the stimuli were music and female speech.

Taken together, the evidence reported by Kuk et al. (2006; 2007) and Auriemmo et al. (2009) suggests that the Audibility Extender is capable of restoring audibility of high-frequency environmental sounds in a manner which is acceptable to both children and adult listeners. The results also indicated that subjective preferences seem to increase with experience.

CONCLUSIONS

The articles reviewed report evidence for the effectiveness of linear frequency transposition in restoring the audibility of high-frequency speech and environmental sounds to hearing aid users with high-frequency hearing loss. Speech perception and production has been found to improve with the Audibility Extender feature in children and adults with gradually or precipitously sloping high-frequency hearing loss. Improvements in speech perception have also been reported for young people with severe to profound hearing loss across the entire frequency range.

Positive outcomes in the form of subjective preference for listening to environmental sounds with the Audibility Extender feature activated have also been identified in both children and adults.

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