Frequency Lowering Technologies: Overview and Introduction to Panel Session

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Overview

Infants and children who have permanent hearing loss from an early age rely on well-fitted, consistently-worn hearing aids to support their learning of the sounds of speech. A well-documented challenge in providing full access to speech sounds is the limited bandwidth of hearing aids. Typical hearing aid frequency responses roll off in the high frequencies, interacting with the often sloping configuration of sensorineural hearing loss to limit access to the portion of the speech signal that is highest in frequency.

Previous publications and presentations at this conference have made it abundantly clear that limited bandwidth harms children's ability to hear, understand, and use certain high-frequency speech sounds (for reviews, see Stelmachowicz, Pittman, Hoover, Lewis and Moeller 2004; Pittman in this volume). These studies have shown that children have more difficulty in limited-bandwidth listening tasks than adults, and that children with hearing loss have more difficulty than their normally hearing peers. The speech stimuli in these studies have often focused on nonwords with high-frequency emphasis, including such phonemes as /ʃ/, /s/, /f/, and /Θ/. With significant energy peaks above 4000 Hz, these stimuli are significantly affected by limitations to bandwidth.

In the current era of hearing technologies, the bandwidth of digital hearing aids is increasing. With advances in digital signal processing, the upper limit of digital processing has evolved, increasing to approximately 10,000 Hz in current instruments. In our experience, this has had a positive impact for fitting to moderately high-frequency targets in the 2000 to 4000 Hz region, particularly for hearing losses that are moderately severe or milder. However, the limitations of the hearing aid receiver have not yet been overcome, and still exert a significant influence on the audible bandwidth of speech at least for severe hearing losses. An example of this is shown in figure 1. Two different current hearing instruments were selected, fitted and fine tuned to the best possible fit for a hearing loss with severe to profound detection thresholds in the mid- to high-frequencies. For conversation-level speech, targets are met only to 2000 Hz, and the peaks of conversation-level speech would likely be audible only to about 2500 Hz (not shown on this figure). High-level sounds are audible to approximately 4000 Hz. Both instruments provide essentially

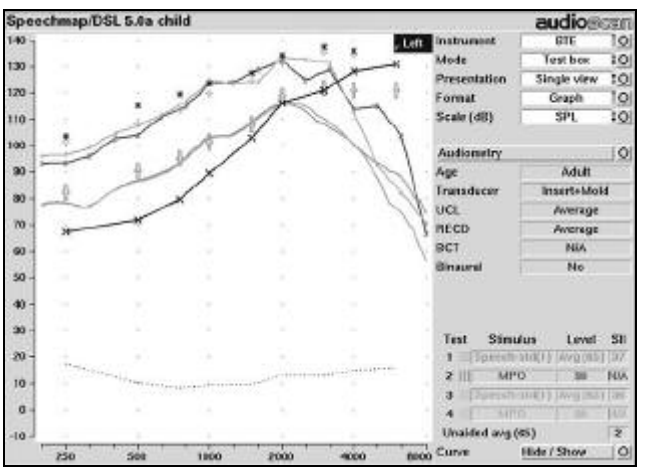

Figure 1. Aided verification of two hearing aid fittings using modern technology.

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the same best fit to targets, despite having digital signal processing bandwidths that far exceed this 2500 Hz - 4000 Hz limitation. As stated above, this limitation is due to the hearing aid receiver, and therefore cannot be overcome by advances in digital signal processing. This fitting would likely not be successful at transmitting the sound /s/ to the child. Even if the receiver limitations could be overcome, would the child's hearing be able to support perception at 3000 Hz and above?

Frequency lowering technology was originally suggested as a means of overcoming the many challenges in providing audibility for a broad range of speech sounds for those with severe to profound hearing losses. Frequency lowering technologies use signal processing to lower the signal in the frequency domain. This has several theoretical advantages: (1) high-frequency speech energy is lowered to a frequency region in which the hearing aid may have more gain; (2) high-frequency speech energy is lowered to a frequency region in which the ear may have a better ability to transduce the signal to neural energy.

Specific frequency lowering technologies have been developed, including those that use frequency *transposition* and those that use nonlinear frequency *compression*. For a detailed review of these technologies, see Simpson (2009). Some of the differences between these two types are illustrated in figure 2. Frequency *transposition*, as currently applied in the Widex AudibilityExtender®, selects the dominant peak in the high-frequency area, and transposes it to a lower frequency by one octave (Kuk et al. 2006). The non-peak energy is not transposed and is not included in the aided signal. The transposed energy is mixed with the non-transposed energy below the cut-off frequency (CF).

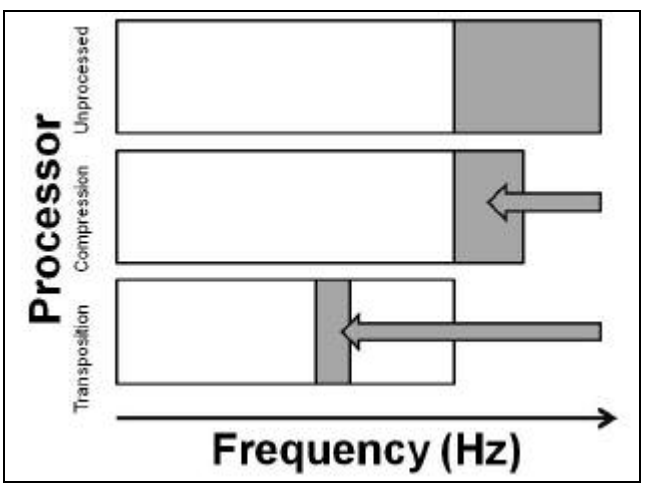

Figure 2. Conceptual illustration of two frequency lowering technologies (frequency transposition, frequency compression) versus unprocessed speech. The shaded grey area represents a clinician-specified high-frequency speech area, and the arrows represent the frequency lowering effect.

An alternative to frequency transposition is frequency *compression* (Simpson et al. 2005, 2006). This processor is currently available as Phonak SoundRecover®. It also uses a two-channel strategy. Unlike two-channel transposition, the frequency-compressed energy is not mixed into the low-frequency channel. Instead, the upper channel is compressed in the frequency domain, thereby lowering high-frequency energy but keeping it within the upper channel. The process of frequency compression alters the harmonic relationships within the compressed channel. Frequency compression is applied along a nonlinear scale, resulting in the most frequency lowering effect for the highest frequencies; energy just above the CF receives very little frequency lowering (Simpson 2009).

Both types of commercial product allow the clinician to adjust the amount of frequency lowering and the frequency range that is selected to be lowered. The issue of fitting and optimization is therefore something that is of great clinical interest and is likely an important factor in studies of aided benefit with these technologies.

Both frequency transposition and frequency compression have been studied in adults and children. Pediatric studies of frequency transposition include both older (MacArdle et al. 2001; Miller-Hansen, Nelson, Widen and Simon 2003) and current technologies. Pediatric trials of currently available frequency lowering technologies have been published, both for the frequency transposition type (Auriemmo et al. 2009; Smith, Dann and Brown 2009), and the frequency compression type (Glista et al. 2009a; Glista, Scollie, Polonenko and Sulkers 2009b; Wolfe et al. 2010, 2011).

Frequency transposition hearing aids have been evaluated in two pediatric studies (Auriemmo et al. 2009; Smith et al. 2009). Smith and colleagues (2009) studied six students with severe or profound high-frequency hearing losses. The hearing instruments were fitted using product-specific in situ audiometry with real ear live speech mapping. No specific target level of audibility for the live speech was defined, and the authors stated that fine tuning attempted to ensure audibility of speech at 2000 Hz. Responses were further adjusted in relation to user comments. User-driven tuning resulted in additional gain being applied in the transposed versus non-transposed setting in all cases. The transposition plus

gain fitting was then evaluated versus the default fitting. Results indicated significant improvements for phoneme recognition (audition only) and on the Goldman-Fristoe 2 Test of Articulation. Improvements were substantial for three of the six children. The authors provide clinical discussions of their use of venting for children with good low-frequency hearing, decisions around fitting an asymmetrical hearing loss, and the role of degree of hearing loss in the high frequencies, perhaps reminding us that frequency lowering technologies are used in combination with other attributes of the fitting.

Auriemmo and colleagues (2009) evaluated frequency transposition on ten children who had thresholds of 70 dB HL or poorer at 2000 Hz and above. The hearing instruments were fitted to DSL 5.0 targets (Scollie et al. 2005) in the Audioscan Verifit®, although audibility above 3000 Hz was not attempted, assuming that the hearing losses were too severe to benefit. Single blinding was used to prevent the children or parents from being aware of the use of the transposition processing within the study aids. Frequency lowering and gain for the transposed signal were adjusted iteratively until the child reported hearing a recorded sample of /s/ or /ʃ/. The study hearing instruments were fitted first without frequency transposition (three weeks), then with transposition (three and six weeks). Training was provided throughout both treatment phases. Outcome evaluation was performed both at day of fitting and after the trial period for both hearing aid programs. Significant improvements were measured for aided sound field-thresholds from 1000 through 4000 Hz, and nonsense syllable scores following the frequency transposition plus training trial versus the default fitting plus training. Individual analyses indicated that the poorer the child's performance without transposition, the more benefit was obtained with transposition. Subjective measures indicated that the children tended to prefer the aids with transposition activated, and that their production of the phonemes /s/ and /z/ improved following the transposition plus training trial period.

The studies of frequency compression hearing aids have tested children with severe to profound hearing loss, but also children with moderate and moderately severe hearing loss (Glista et al. 2009a; Wolfe et al. 2010, 2011). Glista and colleagues (2009a) tested a group of eleven children with high-frequency hearing losses ranging from mild through profound, along with a control group of audiometrically similar adults. Prototype hearing instruments were fitted using the Audioscan Verifit® and DSL 5.0 targets, with the attempt to provide the broadest possible audible bandwidth in the program without frequency compression. Frequency compression was applied and individually fine tuned to maximize audibility of /ʃ/ and /s/ sounds. The gain of the hearing aid was held constant between the programs with and without frequency compression, and parents, children and administrators of subjective questionnaires were not aware of which setting used the frequency compression processing. Hearing aids were worn first with, then without frequency compression for trial periods lasting a minimum of four weeks, and no additional training was provided. Objective outcome measures were obtained in a withdrawal design to place any advantage of experience upon the condition without frequency compression. Significant improvements were reported for the frequency compression condition for speech sound detection, high-frequency nonsense syllable recognition, word-final plural detection, and blinded preference. Individual analyses indicated that frequency compression benefit was related to magnitude and configuration of hearing loss, as well as age group: children were more likely to prefer and benefit from the processor. In a follow-up study, testing with most of the same sample of children indicated that the scores obtained with the prototype hearing instruments were also obtained with commercially available devices (Glista et al. 2009b).

Wolfe and colleagues (2010) tested 15 children with hearing losses approximating 60 dB HL in the 300 to 6000 Hz range. Hearing instruments were fitted to DSL v5.0 targets using the Audioscan Verifit®, and the frequency compression settings were tuned until a one-third octave band of speech at 6300 Hz was above threshold. Outcomes were evaluated following a six week trial without and with frequency compression, with half of the participants starting with and the other without the processor activated. Outcomes following six months of use are reported in a companion chapter (Wolfe et al. 2011). Outcomes after six weeks indicated significant improvements with frequency compression for aided thresholds, word-final plural detection, and aided phoneme recognition, with no advantage or disadvantage for a test of sentence recognition in noise. The results of these studies are summarized in further detail in a companion chapter by Wolfe in this volume.

These studies of frequency lowering technologies provide early and promising evidence that frequency lowering may be an effective option for providing audibility of high-frequency speech sounds, for children with hearing loss. The studies are few, however, and firm conclusions about candidacy between the two types of fre-

quency lowering are more elusive. All authors indicate that audiometric configuration may be a critical consideration, both for candidacy and outcomes and also for optimization of settings for individual children. At least two studies (Smith et al. 2009; Wolfe 2010) discuss specific venting strategies employed to ensure acceptable low frequency acoustic transparency for those children with normal low frequency hearing.

Research Design Considerations

Because the study of frequency lowering technology for children is a relatively new area, experimental design considerations are likely still in evolution. Therefore, it may be wise to revisit some aspects of experimental design that are particularly relevant to effectiveness and efficacy studies of frequency lowering. These relate to the design of the baseline trial to which the frequency lowering program will be compared, the hearing instruments used, the fitting strategies applied, the use of an acclimatization period, and the construction of the test battery. These concepts are illustrated in figure 3.

The "baseline", "conventional" or "default" program is the control condition of interest in frequency lowering research: does the program that uses frequency lowering provide better outcomes than the program that does not? In some studies, the gain by frequency within this control program is optimized in an attempt to provide the best possible fitting. This stringent approach ensures optimal experimental control, ensuring that the frequency-lowered condition is truly responsible for any changes in benefit. However, as hearing instrument technology evolves, the criteria for a "best" fitting may also change: this may impact interpretation of studies across time, and is more likely to affect milder gain fittings before high power fittings as the latter are more likely to be limited by the hearing instrument receiver.

The hearing instrument itself plays a role in experimental control. A participant's own hearing aids may be fitted differently, or be of different technology than the experimental devices, leading to different outcomes between instruments. This is seen, for example, in results from Auriemmo et al. (2009), in significant differences between participant's own aids and the control fitting of the study hearing aids. Minimally, tests of own aids versus experimental aids should ensure that the frequency responses of the two devices are matched.

Fitting considerations for any hearing aid study should ensure that the hearing aid is appropriately and individually fitted. In addition, studies of frequency lowering must adjust the amount and degree of frequency lowering for the hearing loss and listening needs of each participant. Unfortunately, validated fitting and fine tuning prescriptions are not yet available for these new technologies. However, systematic fitting tools and fitting goals are available, and are described in some detail in the research studies published to date and in tutorial articles (Glista and Scollie 2009; Scollie, Glista, Bagatto and Seewald 2007). One such tool is a filtered speech signal that allows measurement of the aided levels of a one-third octave band of speech. When tested both with and

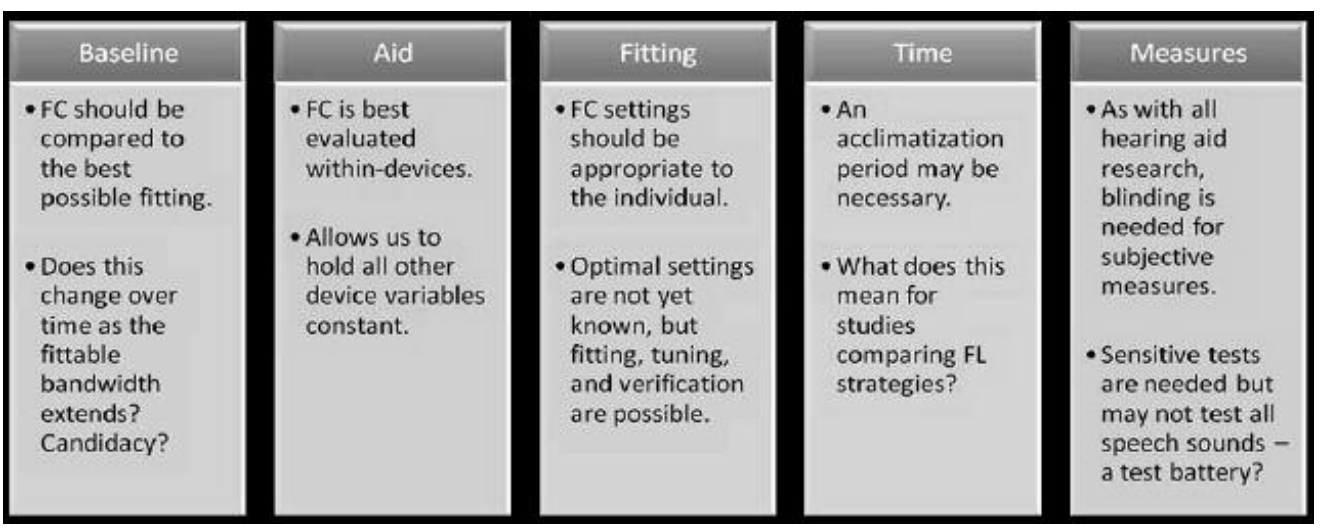

Figure 3. Some experimental considerations when designing or evaluating research studies of frequency lowering effectiveness or efficacy.

without frequency lowering, this test signal allows direct comparison of the frequency lowering effect. Examples of the use of this test are provided in companion chapters in this volume by Glista et al. and Wolfe. Case studies illustrating the fitting and outcome profiles of children with vastly different audiometric configurations are also provided in a separate companion chapter by Bohnert et al. in this volume.

Following experimental fittings, it is common across studies to provide a period of acclimatization. The studies summarized above have used trial periods ranging from three weeks to six months. The exact time course of acclimatization is not yet known, but it is reasonable to assume that a period of acclimatization is necessary. A case study in a companion chapter explores this issue in more detail (Glista et al. in this volume). A more complex issue is whether to study frequency lowering along with training, which may maximize adjustment to the processed sound, or in isolation, which provides greater experimental control. One area of research needed is to contrast these two approaches, in order to better understand the separate contributions of training versus processing.

Outcome test batteries across studies tend to include a wide range of outcome measures, ranging from simple detection tasks, to speech sound detection and word recognition, to sentence in noise recognition, subjective preference and speech production. Use of a broad range of outcome measures allows exploration of the impact of a processor on various aspects of hearing aid outcome. However, the development of sensitive and specific measures of high-frequency speech sound recognition is also a priority, as discussed in a companion chapter (see Boretzki et al. in this volume). For subjective outcome measures such as questionnaires, outcomes may be influenced by a labeling effect, similar to the placebo effect in pharmaceutical research. Merely telling research participants that a hearing aid uses new processing or is "digital" versus "analog" can significantly increase subjective scores (Bentler, Niebuhr, Johnson and Flamme 2003). This consideration may also apply to the evaluation of specific processing technologies. Studies therefore employ multi-memory evaluations in which the frequency lowering technology is applied in one memory, without the participant's awareness. A further step may be to prevent clinicians who administer questionnaires from being aware of the processing status of the current trial memory under evaluation.

Panel Session

This chapter has summarized current knowledge on frequency lowering technology, and its application in children. Arising from a panel session at the conference, several companion chapters provide more detailed discussion of specific research studies and specific case examples from children who wore, and who completed outcome test batteries with, frequency compression hearing instruments (Bohnert et al., Glista et al. and Wolfe, all in this volume). The insights contained within these companion chapters illustrate key concepts in fitting, acclimatization, the role of dead regions, and the role of magnitude and configuration of hearing loss. We have much more to learn about frequency lowering technology, but it is encouraging that much more is known than was just a few short years ago. Please consider results that these panel members have shared: panel members specifically chose to present specific cases at the individual level. As such, this group of chapters provides research data but also provides clinical insight into our fitting practices. Enjoy!

Acknowledgements

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