Perceptual Acclimatization Post Nonlinear Frequency Compression Hearing Aid Fitting in Older Children

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Purpose: In this study, the authors evaluated the effect of frequency compression hearing aids on speech perception ability and the time course and magnitude of acclimatization-related changes.

Method: Participants included children ages 11–18 years. Speech perception ability was evaluated over well-controlled baseline, treatment, and withdrawal study phases. Study-worn hearing aids were individually fitted to all participants. The authors evaluated speech perception ability using outcomes of speech detection (/s/ and /S/ sounds), /s–S/ discrimination, and plural and consonant recognition.

Results: Indices of change were discussed on a case-by-case basis across all study phases. Significant treatment effects were measured for all cases, on at least one measure, with some listeners displaying significant acclimatization trends following a trial of frequency compression.

Conclusion: Findings suggest that frequency compression provided varying outcomes, both in benefit and acclimatization, across listeners. For some, a period of acclimatization was necessary before change could be measured. For others, performance remained stable over the time course under evaluation, suggesting that some but not all children will experience improved speech recognition ability after a period of frequency compression hearing aid use.

Key Words: hearing aids, hearing device evaluation, children, single-subject design

Rehabilitation for listeners with hearing impairment (HI) often includes the provision of amplification via hearing aids. When conventional hearing aids are not able to provide audibility of high-frequency speech sounds, frequency-lowering signal processing is a clinically available treatment option. In this study, we evaluated the time course of acclimatization to a frequency-lowered signal over several months of real-world use.

For adult listeners with severe-to-profound high-frequency hearing loss, the gain needed to provide audibility of high-frequency speech sounds does not always translate into better speech perception performance. Several studies suggest that amplification at frequencies where hearing impairment is severe provides little to no speech perception benefit (Ching, Dillon, & Byrne, 1998; Ching, Dillon, Katsch, & Byrne, 2001; Hogan & Turner, 1998). Others have suggested that providing high-frequency information to listeners with high-frequency hearing loss can significantly improve speech perception, especially in noisy listening environments (Plyler & Fleck, 2006; Turner & Henry, 2002). However, individual variability in these studies suggests that some listeners receive speech perception benefit from amplified high-frequency sound, whereas others do not. For the pediatric population, both age and hearing loss have been shown as significant predictors of speech recognition measured in both quiet and noise (Scollie, 2008; Stelmachowicz, Hoover, Lewis, Kortekaas, & Pittman, 2000).

Listeners with high-frequency cochlear dead regions may experience a lack of benefit with high-frequency audibility (see review in Moore, 2004); this may vary across listeners and has largely been studied in the adult
population (Cox, Alexander, Johnson, & Rivera, 2011). Studies including both adults and children have suggested that hearing aids with frequency-lowering technology could be considered for listeners with significant dead regions (Vickers, Moore, & Baer, 2001) and/or for listeners with severe high-frequency hearing loss (Glista, Scollie, Bagatto, et al., 2009; Robinson, Stainsby, Baer, & Moore, 2009).

Some clinically available types of frequency-lowering hearing aid technology include nonlinear frequency compression and frequency transposition. Studies suggest that these frequency-lowering technologies may benefit adults and children with high-frequency hearing loss, and that benefit varies across individuals (see review by Simpson, 2009). In general, frequency compression splits the incoming hearing aid signal into two channels. The high-frequency channel is compressed into a narrower bandwidth. This results in sound being lowered in frequency within the high-frequency channel (Simpson, Hersbach, & McDermott, 2005). Research suggests that frequency compression provides speech perception benefit for some adults and children with high-frequency hearing loss (Bohnert, Nyffeler, & Keilmann, 2010; Glista, Scollie, Bagatto, et al., 2009; Simpson et al., 2005; Simpson, Hersbach, & McDermott, 2006; Wolfe et al., 2010). In previous studies of frequency compression, researchers have examined varying degrees/configurations of high-frequency hearing impairment, fitting approaches, and listening environments. Research suggests that candidacy may be affected by both audiometric configuration and age group, with both children (versus adults) and listeners who have greater high-frequency hearing loss being more likely to receive benefit (Glista, Scollie, Bagatto, et al., 2009).

Auditory Acclimatization Post Hearing Aid Fitting

For listeners with longstanding severe-to-profound high-frequency hearing losses, frequency-lowering hearing aids may provide access to new high-frequency cues, albeit presented at lower frequencies. When the auditory system receives this new acoustic information, some time for learning-induced reorganization may be required to accommodate novel sounds. This adjustment period has been defined as auditory acclimatization (Arlinger et al., 1996), as reported in the Eriks Holm Workshop on Auditory Deprivation and Acclimatization (1996): "Auditory acclimatization is a systematic change in auditory performance with time, linked to a change in the acoustic information available to the listener. It involves an improvement in performance that cannot be attributed purely to task, procedural or training effects" (p. 87S).

The role of auditory acclimatization post hearing aid fittings has been a topic of interest in the literature for many years. The evidence presented in the older research is mixed. In several studies, researchers concluded that the acclimatization effect is minimal and may vary according to measurement technique, practice effects, and/or changes made to hearing aid gain within a study (Bentler, Niebuhr, Getta, & Anderson, 1993; Flynn, Davis, & Pogash, 2004; Humes, Halling, & Coughlin, 1996; Saunders & Cienkowski, 1997; Sur, Cord, & Walden, 1998; Turner, Humes, Bentler, & Cox, 1996). Alternatively, several studies have reported change in benefit over time in the range of 0% to 10%, with some individuals demonstrating larger improvement (Arlinger et al., 1996; Cox, Alexander, Taylor, & Gray, 1996; Gatehouse, 1992, 1993; Horwitz & Turner, 1997; Kuk, Potts, Lee, Valente, & Piccirillo, 2003; Silman, Silverman, Emmer, & Gelfand, 1993; Yund, Roup, Simon, & Bowman, 2006). In all of the studies noted above, experimenters tested adult subjects, with one exception—the study by Flynn and colleagues, in which the authors concluded that that the trend in improved speech perception over time likely related to fine-tuning modifications made over the course of the study rather than an acclimatization effect. Overall, individual variability in acclimatization post hearing aid use may relate to factors including hearing loss severity/configuration, age, cognitive ability, hearing aid experience, hearing aid style, and the complexity of the hearing aid signal-processing scheme (Bentler et al., 1993; Cox et al., 1996; Gatehouse, 1992; Horwitz & Turner, 1997; Saunders & Cienkowski, 1997; Yund et al., 2006).

Data regarding adult–child differences in post hearing aid acclimatization patterns are not readily available, although auditory learning studies in listeners with normal hearing indicate that maturation of auditory learning continues to develop through adolescence (Huyck & Wright, 2011). These studies are consistent with maturation of auditory evoked potentials, in which maturation may occur by age 6 years or continue to approximately age 12, depending on the methodology (Pang & Taylor, 2000; Ponton, Eggermont, Kwong, & Don, 2000; Wunderlinch & Cone-Wesson, 2006). Overall, research suggests that maturation related to auditory processing skills, such as speech recognition, may continue into adolescence. This evidence is consistent with the idea that children may not show the same acclimatization patterns as adults. In addition to maturation effects, generalization of auditory learning may be both task and stimulus dependent (Wright & Zhang, 2009). In general, frequency resolution abilities tend to mature earlier (Hartley, Wright, Hogan, & Moore, 2000) and generalize outside of trained tasks (Wright & Zhang, 2009), compared with temporal abilities.
Auditory Acclimatization and Frequency Lowering

Current research suggests that acclimatization may play a role in speech perception performance with frequency-lowering technologies. Wolfe and colleagues (2010, 2011) formally evaluated the long-term effects of frequency compression in children ages 5–13 with moderate to moderately severe hearing loss at 6 weeks and 6 months post fitting. Results varied across the different speech measures used in the study. Aided detection results improved with frequency compression and remained stable over the 6-month time course. Recognition of word-final plurality improved with frequency compression; however, high performance levels limited measurement of long-term acclimatization effects. Nonsense syllable recognition was significantly better at the 6-month period when compared with conventional processing and after 6 weeks of frequency compression use. Last, frequency compression offered improved speech recognition in noise after several weeks to several months of use. Because there was no control group, Wolfe and colleagues could not determine whether the improvement in recognition of speech sounds over time should be attributed to a learning effect, acclimatization, or both. The authors pointed out the possibility that improvements measured over time may have been, in part, due to linguistic and/or cognitive maturation, on the basis of the study length and the children’s ages (Wolfe et al., 2011). Additional studies on the effects of frequency lowering with children have suggested that benefit may vary with acclimatization time (Auriemma et al., 2009; Glista, Scollie, Bagatto, et al., 2009; Glista, Scollie, Polonenko, & Sulkers, 2009; Wolfe et al., 2010). Further research is needed to examine the time course of acclimatization effects on perceptual benefits of frequency-lowering technology.

The Current Study

This study was designed to examine the time course of acclimatization to frequency-lowering hearing aids. We recruited a group of older HI children and followed them for 6 months of hearing aid use. We selected this age range of children to minimize expected maturational confounds. We chose this age range on the basis of studies related to the maturation of auditory-evoked potentials (described above) in the absence of direct evidence related to adult–child differences in post-hearing-aid acclimatization patterns. Speech perception measures were administered on 10 different testing appointments spanning baseline, treatment, and withdrawal phases. We used a single-subject design; each participant acted as his or her own control. In this study, we evaluated the effect of nonlinear frequency compression hearing aids on speech perception ability and the time course and magnitude of acclimatization-related changes following a real-world trial.

Method

Participants

Recruitment of six participants ages 11–18 years took place at the University of Western Ontario (UWO) H. A. Leeper Speech and Hearing Clinic, local audiology clinics, and through an educational audiologist. Participants who met the inclusion criteria for the study were enrolled in a sequential manner; recruitment efforts were limited to a smaller number of participants, facilitating a single-subject design. The feasibility of collecting data from a larger number of participants was limited due to challenges encountered when conducting repeated outcome measurement over an extended time course. No participant was excluded on the basis of task performance or degree of benefit. For binaurally aided participants, audiometric inclusion criterion were as follows: a bilateral sensorineural hearing impairment, sloping to at least a moderately severe high-frequency pure-tone average (HP-PTA) hearing level averaged across 2000 Hz, 3000 Hz, and 4000 Hz.

Participants were required to be full-time users of digital behind-the-ear (BTE) hearing aids prior to entering the study. Five of the participants wore binaural hearing aids and had high-frequency losses that were symmetrical within 10 dB on the basis of HF-PTA. One participant with an asymmetrical hearing loss was monaurally aided in the better ear (Case 6). On average, the participants began wearing hearing aids at age 3.75 years, as per parental report. Details pertaining to previously worn hearing aid type, fit-to-targets, and FM usage are reported in Table 1. A data-logging feature tracked hearing aid usage over the course of the study on all study-worn hearing aids. All participants were assessed as full-time hearing aid users (i.e., achieving continuous usage during school hours) prior to beginning data collection. The UWO Research Ethics Board approved this study for health sciences research involving human subjects.

Pure-tone air conduction thresholds were measured bilaterally at all octave and interoctave frequencies between 250 Hz and 8000 Hz for each participant using a Grason–Stadler 61 audiometer. Air conduction threshold testing was completed in a double-walled sound-treated booth using Etymotic Research ER-3A insert earphones coupled to each participant’s personal earmolds. We measured hearing thresholds at the beginning and end of the study; all participants demonstrated hearing levels within 10 dB of baseline over the course of the study.
Participants were evaluated for cochlear dead regions (DRs) through use of the threshold equalizing noise (TEN-HL) test; results were interpreted through use of published criteria (Malicka, Munro, & Baker, 2010; Moore, 2004; Moore, Glasberg, & Stone, 2004). Refer to Table 1 for demographic and TEN test results. This test supports measurements up to 4000 Hz. Suspected DRs are reported according to TEN test results; in some cases, no DRs were measured (denoted with “none”) or hearing threshold levels were beyond the range of the TEN-HL test (denoted with “INC”). Participants are listed from least to greatest HF-PTA.

### Table 1: Summary of case history, audiometric assessment, fit-to-targets (for previously worn hearing aids and conventional study-worn hearing aids), frequency compression settings, and verification across cases.

<table>
<thead>
<tr>
<th>Case</th>
<th>Age</th>
<th>Test ear</th>
<th>Previous HA make/model</th>
<th>Previous FM use</th>
<th>PTA (dB HL)</th>
<th>HF-PTA (dB HL)</th>
<th>Slope (dB HL)</th>
<th>Hearing loss dropoff (Hz)</th>
<th>DR(s) (kHz)</th>
<th>Fit-to-targets (kHz)</th>
<th>NLFC ratio</th>
<th>NLFC audibility (kHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>15</td>
<td>R</td>
<td>Bernafon/Neo</td>
<td>Y</td>
<td>18</td>
<td>67</td>
<td>65</td>
<td>3000</td>
<td>None</td>
<td>1500</td>
<td>3.2</td>
<td>2.4:1</td>
</tr>
<tr>
<td>2</td>
<td>18</td>
<td>L</td>
<td>Siemens/Centra</td>
<td>Y</td>
<td>42</td>
<td>90</td>
<td>95</td>
<td>2000</td>
<td>None</td>
<td>2000</td>
<td>2.2</td>
<td>4:1</td>
</tr>
<tr>
<td>3</td>
<td>18</td>
<td>L</td>
<td>Bernafon/Flair</td>
<td>Y</td>
<td>75</td>
<td>93</td>
<td>35</td>
<td>500</td>
<td>None</td>
<td>1500</td>
<td>2.1</td>
<td>4:1</td>
</tr>
<tr>
<td>4</td>
<td>11</td>
<td>R</td>
<td>Phonak/411</td>
<td>Y</td>
<td>52</td>
<td>100</td>
<td>105</td>
<td>1500</td>
<td>2, 3, and 4</td>
<td>1500</td>
<td>1.6</td>
<td>4 only</td>
</tr>
<tr>
<td>5</td>
<td>14</td>
<td>L</td>
<td>Phonak/Piconet2</td>
<td>Y</td>
<td>72</td>
<td>110</td>
<td>70</td>
<td>750</td>
<td>None</td>
<td>750</td>
<td>1.8</td>
<td>4:1</td>
</tr>
<tr>
<td>6</td>
<td>18</td>
<td>R</td>
<td>Phonak/Novo-Forte</td>
<td>N</td>
<td>83</td>
<td>117</td>
<td>60</td>
<td>1000</td>
<td>INC at 3 and 4</td>
<td>750</td>
<td>1.6</td>
<td>3.6:1 no</td>
</tr>
</tbody>
</table>

Note. Pure-tone-average (PTA), high-frequency PTA (HF-PTA), and hearing loss slope are reported in dB HL. Audiometric dropoff frequency is defined by the frequency at which thresholds met or exceeded 70 dB HL. Suspected or inconclusive (INC) cochlear dead regions (DRs) and are reported according to TEN test results. The upper frequency limit of fit-to-targets within ±5 dB for a 70 dB SPL input level (DSL v5.0 child prescription) is reported for previously worn hearing aids (left stubhead column titled “Previous” and study-worn hearing aids (right stubhead column titled “Study”). The upper limit of high-frequency (HF) audibility with nonlinear frequency compression (NLFC) is reported for filtered speech stimuli (Audioscan Verifit VF-1) centered on 4000 and 6300 Hz for an input level of 70 dB SPL. R = right; L = left.

### Hearing Aid Fitting

Device fitting followed protocols from the Desired Sensation Level (DSL) method Version 5.0 (Bagatto et al., 2005; Scollie et al., 2005) as implemented within the Audioscan Verifit VF1. Each participant was fitted with study-worn hearing aids: Phonak Naida IX SP BTE hearing aids coupled to integrated FM receiver boots (MicroLink ML10i); these devices were worn for the entire duration of the study with the gain/advanced features of the devices held constant throughout. We disabled the volume control (VC), digital noise reduction (DNR), and automatic program selector features in the main listening program. Prescriptive targets were matched using simulated real-ear measures incorporating individual real ear to coupler difference (RECD) values. We selected a coupler-based verification strategy to reduce room noise/reverberation effects and concerns with feedback during real-ear procedures; this promoted test environment consistency and replicable measures across the repeated fitting appointments. Aided measurements of speech at 55 dB SPL, 65 dB SPL, 70 dB SPL, and 75 dB SPL, and for a 90 dB SPL pure-tone signal were completed during fitting appointments. Hearing aids were adjusted so that the best possible match to targets would be provided. When required, participant-driven gain adjustments took place, and only prior to beginning the baseline condition. Reported fit-to-targets data reflected measurement made at the settings worn for this study including any participant-requested gain adjustments. Table 1 includes a summary of the fit-to-targets per child, indexed as the highest frequency at which prescriptive targets could be met within 5 dB for a 70 dB SPL input level. The baseline condition began once this fitting process was completed.

Following the baseline condition, frequency compression parameters were individually adjusted according to a previously established protocol (Glista & Scollie, 2009; Glista, Scollie, Bagatto, et al., 2009), described briefly here. Gain and amplitude compression were held constant to match those of the baseline fitting. Better-ear hearing thresholds were used in the selection of frequency compression settings. The settings were then applied binaurally; in this study, we did not investigate the use of asymmetrical settings. Verification of frequency compression used filtered speech passages available in the Audioscan Verifit VF-1. These passages are shaped to include low-frequency energy, a notched mid-frequency area, and a 1/3 octave band of high-frequency speech energy. This high-frequency band is clinician-selectable, and it centered on frequencies at 3150 Hz, 4000 Hz, 5000 Hz, or 6300 Hz. When tested with frequency compression off versus on, the clinician can observe the frequency location and audibility of the speech band (Bentler, 2010; Glista & Scollie, 2009). We measured the bands...
centered on 4000 Hz and 6300 Hz at an input level of 70 dB SPL and assessed whether they were audible. We enabled and adjusted frequency compression until they were audible or until the limits of adjustment were reached (refer to Table 1 for case-specific results). This type of measurement does not take into account the bandwidth of frication sounds. For this reason, fitted-vocalized sustained fricatives (/s/ and /ʃ/) were used in aided response measurements through the Verifit “live-speech” mode. This allowed an evaluation of the frequency overlap of the frication bands. Fitting adjustments were made to minimize /s-ʃ/ overlap, if possible, in an attempt to provide a fitting that minimized the risk of /s-ʃ/ confusion.

**Outcome Measures**

We administered four aided behavioral outcome measures: (a) speech sound detection, (b) plural recognition, (c) /s-ʃ/ discrimination, and (d) consonant recognition. The first three measures assessed detection or discrimination of high-frequency speech sound (for sensitivity in the frequency range of the processor), and the fourth assessed recognition of a broad range of speech sounds (to provide a more generalizable assessment of speech sound recognition). Test stimuli were presented monaurally to the better-hearing ear according to preference and HP-PTA values. For discrimination and consonant recognition tasks, we varied presentation levels between 55 dB SPL and 70 dB SPL re: the 2cc coupler across cases to ensure testing above chance performance in the baseline condition, but presentation levels were held constant thereafter. The plural recognition task was presented at 55 dB SPL on the basis of procedures from previous studies (Glista, Scollie, Bagatto, et al., 2009; Wolfe et al., 2010). The speech sound detection task was adaptive by level. Counterbalancing was used during outcome measure presentation, per test session. Calibration was performed in the coupler using a hearing aid programmed to have no gain.

Outcome measures were implemented in custom-made experimental software, executed from a personal computer. A computer monitor, positioned in front of each participant, displayed response choices that the participant selected via the use of a mouse. Signals, in the form of .wav files, were routed from the computer to a custom-made programmable attenuator (CM108AH audio chip and LM1973 audio attenuator) and a clinical audiometer (GSI-61). Signals from the audiometer were presented through a modified direct-audio-input (DAI) connector cord connected to the hearing aid.

**Speech sound detection.** We measured aided detection thresholds for speech sounds using an adaptive, computer-controlled version of the Ling Test (Ling, 1988; Tenhaaf & Scollie, 2005). Stimuli, spoken by a female talker, were presented in isolation through the use of a starting presentation level of 70 dB SPL. Threshold values were estimated as the average level of four reversals to a 50% detection criterion. A 10-dB step size was used in the first reversal, followed by a 4-dB step size for all subsequent reversals. These parameters of the adaptive testing procedure remained constant throughout testing. The detection procedure was administered twice for each phoneme across all testing phases. Phonemes were tested in a random order per administration.

Traditionally, the Ling Test is composed of six sounds: /m/, /a/, /i/, /u/, /ʃ/, and /s/. Aided thresholds measured with these sounds: /ʃ/ and /s/. A 1/3 octave band spectral analysis of the stimuli is provided in Figure 1a. Spectral peaks reside at approximately 6000 Hz for /ʃ/ and 2500 Hz for /s/. Aided thresholds measured with these two sounds have been used in previous studies of frequency lowering (Glista, Scollie, Bagatto, et al., 2009). In general, this test measures the lowest level at which isolated speech sounds can be heard. When presented in a repeated measures paradigm, this test can provide information concerning a change in hearing level across different hearing aid conditions (i.e., with and without frequency compression). Depending on the hearing level of the listener and/or activation of frequency compression, it is possible that a listener could hear the phonemes in a distorted and/or alternate form. In the case of steeply sloping, severe-to-profound high-frequency hearing loss, audibility of /ʃ/ or /s/ may be limited to only the lower shoulder of the frication band; this means that resulting measured detection thresholds would likely reflect partial audibility of the sound(s) tested.

**Plural recognition.** The UWO Plurals Test (Glista & Scollie, 2012) assesses participants’ ability to use the fricatives /ʃ/ and /s/ as bound morphemes. For this task, we chose stimuli similar to those used in previous research to test sensitivity to high-frequency audibility in children who use hearing aids (Stelmachowicz, Pittman, Hoover, & Lewis, 2002). Stimuli include the singular and plural forms of 15 words: ant, balloon, book, butterfly, crab, crayon, cup, dog, fly, flower, frog, pig, skunk, sock, and shoe. The testing paradigm included the use of computer-controlled software to automate stimulus presentation, presentation of a closed set of responses, and scoring. A 1/3 octave band analysis of the concatenated words and the extracted fricative portion at the end of each word is displayed in Figure 1b. The mean spectral peak of the fricative portion resides at approximately 5000 Hz. Stimulus files were automatically generated via a computer in random order and including two repetitions, generating a score out of 60 items per measurement. Stimuli were mixed with a speech-shaped noise at a
+20-dB signal-to-noise ratio (SNR). The noise was included to mask low-level stimulus offset cues that could have served as a surrogate cue for plural identification. Participants were instructed to pay attention to the stimuli rather than to the noise. Tester observation inferred that the inclusion of low-level noise did not appear to influence the ability of the children to focus on the stimuli of interest. A closed response set was presented on a computer monitor using pictures (from articulation cards; Super Duper Publications [Webber, 1998a, 1998b, 1999, 2000, 2003]) and a corresponding orthographic display. Each response set included the singular and plural form of each target word. Participants were instructed to choose which picture best described what he or she heard.

The UWO Plurals Test has been included in other studies designed to assess the effects of frequency compression hearing aid technology (Glista, Scollie, Bagatto, et al., 2009; Wolfe et al., 2010). Literature on the development and evaluation of this test proposes its use in evaluating the detection of high-frequency fricative sounds in a word-final position. Results obtained in listeners with normal hearing and in listeners with hearing impairment (aided conditions) indicated reliable repeated outcome measurement (Glista & Scollie, 2012).

/s–ʃ/ discrimination. An aided discrimination task, developed at UWO, was included in the test battery to facilitate the measurement of /s–ʃ/ discrimination. This consisted of six consonant–vowel (CV) syllables including high-frequency fricatives coupled to three vowels ranging in articulator dimension (i.e., front–back, high–low). The stimulus set included nonsense CV pairs /si–ʃi/, /sa–ʃa/, and /su–ʃu/, spoken by three adult female talkers. Stimuli were presented in a three-alternative forced-choice paradigm, and participants were instructed to choose the “oddball” item. Each discrimination score included 54 items (18 items × 3 repetitions). Items were randomized and run in a single block at each testing session. Due to the nature of frequency compression hearing aid processing, frequency compression can result in sounds being presented at lower frequencies and/or with an altered spectral shape (when compared with conventional processing). These effects are of particular interest when considering discrimination of /s–ʃ/ with frequency compression because it can modify the spectral shape of /s/, making it appear closer to that of /ʃ/. Results measured with the /s–ʃ/ discrimination may be influenced by factors including degree of hearing loss, previous exposure to partial or full cues of /s/ and /ʃ/ sounds with conventional amplification, and strength of frequency compression settings.

In the development of this task, we chose the /s/ and /ʃ/ sounds to form recordings made in a double-walled sound booth using a studio-grade AKG condenser microphone (C 4000 B). The microphone was connected to a preamplifier and analog-to-digital converter (USBPre) and desktop computer. Recorded files were digitized at a sampling rate of 44100 Hz, using 16-bit resolution. We used the SpectraPLUS FFT Spectral Analysis System to store the resulting file. All stimuli were recorded several times, and final test items were chosen for similarity and neutrality of intonation for each /s–ʃ/ pair. We introduced stimulus-specific variability to minimize the ability to use idiosyncrasies of a specific stimulus for recognition rather than spectral cues, per se. Variation in the spectral energy of the fricatives was achieved through the pairing of consonants with three different vowels (Boothroyd & Medwetsky, 1992). In addition, multiple talkers and repetitions of each utterance were included. We analyzed the CV spectra to determine differences in the spectral energy of /s/ versus /ʃ/ (using Praat software). Specifically, we measured the centroid frequency, or center of gravity of the frication noise (Forrest, Weismer, Milenkovic, & Dougall, 1988), by extracting the fricative portion of the CV stimuli using 1/3 octave bands analysis (SpectraPLUS; see Figure 2). Centroid values range from 2000 Hz to 4700 Hz.
from 8.03 kHz to 10.37 kHz for CVs beginning with /s/, and from 3.81 kHz to 5.98 kHz for CVs beginning with /ʃ/. The spectral peak is estimated at approximately 10 kHz for CVs beginning with /s/ and at approximately 3 kHz for CVs beginning with /ʃ/. These findings are consistent with those reported in the literature describing the spectral peak frequency of female speech: The spectral energy of an /s/ sound peaks at approximately 6–9 kHz for female speech, whereas the spectral energy of /ʃ/ peaks over a range of approximately 3–6 kHz (Boothroyd & Medwetsky, 1992; Pittman, Stelmachowicz, Lewis, & Hoover, 2003).

Consonant recognition. To measure consonant recognition, we used the University of Western Ontario Distinctive Features Differences Test (UWO-DFD; Cheesman & Jamieson, 1996), developed with four talkers and 21 nonsense disyllables, including /b, tʃ, d, f, g, h, dʒ, k, l, m, n, p, r, s, ʃ, t, ð, v, w, j, and z/. We presented all items in a fixed, word-medial context (i.e., ACII). Participants were instructed to select the target nonsense word from an orthographic display on a computer monitor. Presentation of stimuli, recording of responses, scoring, and presentation of results were all under computer control. The final task included 84 items, comprised of tokens spoken by two female talkers and two male talkers. Each phoneme was therefore presented four times in a random order across speakers. We included the UWO-DFD in this study to provide both a general measure of the participant’s abilities to identify consonant sounds and an indication of the types of confusion errors made across the different testing conditions. Previous studies found consonant identification tasks to be sensitive to changes in the patterns of consonant confusions introduced by frequency-lowering technologies (Robinson, Baer, & Moore, 2007; Robinson et al., 2009). This test was included in previous research evaluating aided speech sound recognition in child and adult listeners (Glista, Scollie, Bagatto, et al., 2009; Jenstad, Seewald, Cornelisse, & Shantz, 1999; Scollie, 2008; Scollie et al., 2010).

Study Design and Data Collection Sequence

Case series evaluation was conducted as a withdrawal design, including outcome measures administered repeatedly for two test conditions: evaluation of conventional processing and evaluation of frequency compression. The experiment was sectioned into three phases: (a) Baseline (with conventional processing), (b) Treatment (with frequency compression), and (c) Withdrawal (with conventional processing). Across all conditions, study participants were blind to the status of hearing aid processing. Experimenter bias was minimized through the use of fully automated, computer-controlled testing.

We employed a single-subject design to evaluate change at the level of the individual; this approach was used in prior research on acclimatization effects post hearing aid use (Gatehouse, 1992). This type of research design requires experimental control and rigor, as does group-level design, although the specific experimental parameters differ and are specific to single-subject design (Logan, Hickman, Harris, & Heriza, 2008). In single-subject design, each participant serves as his or her own control, thus allowing researchers the opportunity to measure significant changes in performance at the individual level (Gast, 2010). Achieving this level of control was of particular interest in this study because each participant presented with different hearing loss degrees/configurations, thus requiring different frequency compression settings. In addition, previous studies (Simpson, 2009) have reported large between-subject variability in results obtained with frequency-lowering hearing aids. The use of change indices within single-subject design can facilitate measurement of small, consistent variations in performance level within a testing condition. Such findings may not be as apparent at the group level. Although this type of design offers a way of evaluating clinical significance, the extent to which findings can be applied to HI listeners beyond this study is limited.
Baseline phase. The volume control was disabled during this phase (and all other phases of the study). A minimum of two testing sessions were scheduled for all tasks during the baseline phase. A stopping criterion enabled evaluation of stable performance without frequency compression prior to introducing treatment. Confidence intervals (CIs) were used briefly to judge whether performance across adjacent testing sessions was significantly different; lack of change across adjacent sessions was interpreted as stable performance. The goal of this design was to allow practice and acclimatization time without frequency compression and start the treatment phase once stable baseline performance was achieved.

Treatment phase. This phase included six test sessions—four sessions of outcome measurement completed every 2 weeks, followed by two sessions at monthly intervals. Frequency compression processing was enabled for the first test session and remained enabled without modification across the entire treatment phase. Strict adherence to the intended biweekly/monthly timeline could not be achieved for all participants due to illness and/or scheduling factors. On average, we allotted a 16-week treatment phase to all participants (range = 14.1–17.0 weeks). This time period is consistent with that reported in the literature (i.e., 12–18 weeks) investigating acclimatization effects in aided speech perception (Gatehouse, 1992, 1993; Horwitz & Turner, 1997).

Withdrawal phase. We included a final test session to evaluate performance without frequency compression following acclimatization to frequency compression. We achieved this by disabling the frequency compressor on the final day of testing. All participants wore the study aids with frequency compression enabled until the time of this withdrawal appointment. On average, withdrawal testing was completed 3.5 weeks (range = 1.0–7.4 weeks) after finishing the treatment condition of the study. Details pertaining to the study design and individual results were disclosed to the participants upon completion of the withdrawal phase. The study-worn aids were then offered to all participants free of charge, with the option of reenabling frequency compression and/or incorporating other fitting alterations. All participants chose to keep the study-worn aids with frequency compression enabled; the sole change requested was enabling of the VC.

Analyses included the use of CIs calculated across change indices (Morgan & Morgan, 2009; Portney & Watkins, 2000) and a within-condition approach (Gast, 2010), as described below. Within-condition analyses are traditionally found in single-subject research to analyze the direction of change within a testing condition. All analysis strategies were chosen to facilitate measurement of small, consistent change at the individual level. Indices of change included (a) increased or decreased performance within the baseline condition, (b) overall difference in performance between baseline and treatment, (c) increased or decreased performance during the treatment condition (denoting acclimatization trends), and (d) differences between adjacent scores at the boundaries of the baseline and treatment or treatment and withdrawal conditions. Error pattern analyses were performed for three of the four indices of changes, according to results obtained on the UWO-DFD test. Case-specific results are presented in the order in which they appear in Table 1.

Change within the baseline condition. For each child, CIs were calculated around scores corresponding to each testing session within the baseline condition. This facilitated an evaluation of change across adjacent testing sessions and the use of a stopping criterion. Intervals were computed from the mean baseline score, which is ± 1.96 × the SD of test–retest scores for repeated measures including plural recognition, /s–/f/ discrimination, and detection measures (Portney & Watkins, 2000). For the consonant recognition measure, the SD was calculated from the binomial theorem (Thornton & Raffin, 1978). The length of the baseline condition was determined on a case-by-case basis and according to the following stopping criterion: demonstration that (a) the mean score of the adjacent testing session fell within this CI or (b) the mean score for the adjacent testing session fell below the CI. These simplified CIs (related to test–retest) assisted the tester in deciding when a participant should advance to the treatment phase; this strategy differed from those described below.

We used a CI, derived around the entire baseline phase, to evaluate change attributable to treatment. This interval was calculated as the upper limit of a CI around the mean scores across the baseline phase. CIs were calculated around mean scores according to the binomial theorem for all recognition- or discrimination-based tasks and using a CI of ± 5 dB for detection tasks. This yielded a CI around detection scores larger than the mean baseline test–retest error for this task. Significant change attributable to frequency compression use was observed when two or more consecutive treatment scores fell outside these CIs; this is consistent with established procedures and takes into account that treatment effects are not always stable over a prolonged period of testing (Morgan & Morgan, 2009).

Results

Analysis Strategies

Analyses focused on significant change, both positive and negative, in speech perception performance at the individual level within and across study conditions.
Change within the treatment condition. Additional analyses were performed on scores within the treatment condition in a two-step process for each measure and child; this second step was completed only when the first step yielded a significant result. First, we evaluated the relative change in performance level by subtracting the median value of the last three testing sessions from that of the first three testing sessions; we used median values, rather than mean values, to limit degree of influence from outliers (Gast, 2010). Second, we performed linear and nonlinear regression analyses to further evaluate the acclimatization trend. Data sets displaying a gradual change over time were fitted linearly; results were deemed significant when the slope of the line was significantly different from zero. Data sets displaying improvement after a specific period of time (i.e., S-shaped curves) were fitted with a sigmoidal function using XLfit curve-fitting software (ID Business Solutions, 2009):

\[ \text{Predicted score} = \{D + \left[\frac{(V_{\text{max}} \times x^n)}{(x^n + (K_{\text{m}})^n)}\right]\}, \]

where \(D\) describes the bottom plateau of the curve, \(V_{\text{max}}\) describes the range of performance values the curve takes, \(n\) describes the slope factor, and \(K_{\text{m}}\) describes the \(x\) value at which the middle \(y\) value is attained. Nonlinear analyses were deemed significant when raw data points were strongly correlated to those predicted \((p < .05)\). Trends are plotted for significant cases only (see Figures 3 through 8) and are summarized in Table 2.

Change between adjacent scores: Baseline to treatment or treatment to withdrawal. To evaluate an initial treatment effect, we derived CIs around the final baseline scores; these extended into the treatment phase to include the initial treatment score. We calculated CIs around mean scores according to the binomial theorem for all recognition/discrimination-based tasks and using a CI of ±5 dB for detection tasks. A significant treatment effect (benefit/decrement) was reported when the initial treatment score fell outside the interval. To evaluate the withdrawal effect, we derived CIs around the final treatment score; these extended to include the withdrawal score. Intervals were calculated through use of the binomial theorem for all recognition- or discrimination-based tasks and using a fixed CI of ±5 dB for detection tasks. A significant withdrawal effect (benefit or decrement) was reported when the final score with frequency compression disabled fell outside this treatment CI.

Error pattern analysis. We used raw scores obtained on the UWO-DFD test to generate tables of “difference” confusion matrices, across participants and for the latter three of the changes indices (see the Appendix). The first column of matrices display change in consonant confusions due to initial activation of frequency compression; scores are a result of subtracting final baseline scores from initial treatment scores. The second column displays change within the treatment condition (i.e., acclimatization effects); scores are a result of subtracting initial treatment scores from final treatment scores. The final column displays change due to withdrawal of treatment; scores reflect subtraction of the withdrawal scores from the final treatment scores. Stimuli appear in alphabetic order according to the response options presented to the participants. Interpretation of results falling off the diagonal are as follows: Positive numbers indicate less errors with frequency compression enabled (first and last columns), or an improvement with frequency compression over time (second column only), and negative numbers indicate frequency compression decrement. The opposite can be interpreted for results falling off the diagonal: Positive numbers indicate more errors with frequency compression enabled, and negative numbers indicate fewer errors without frequency compression (compared with either frequency compression or across time). Because of the small sample of results displayed for each participant, this discussion focuses on changes in confusion identification greater than 50% (i.e., a difference value of three or four).

Case Study 1

Case Study 1 is an example of a child who received little benefit from frequency compression and who performed at ceiling on most tests regardless of hearing aid condition. Figure 3 shows the results for the first case, displayed for each measure as a function of time. The vertical lines within each panel delineate the baseline, treatment, and withdrawal phases. Shaded areas represent the CIs. Results without and with frequency compression are plotted as open and filled symbols, respectively. Note that the ordinates for the upper panels (measured in percent correct) and lower panels (measured in dB SPL) indicate performance and threshold measures, respectively. An asterisk and/or a trend line indicates significant effects. Also included in this figure is an audiogram showing the child's hearing thresholds.

Overall, Case Study 1 had high performance scores for the recognition and discrimination tasks across test sessions. Significant initial frequency compression benefit was measured on the /s/ detection task only, which is an adaptive task with the highest frequency stimulus in this battery. Electroacoustically, there was little room for improvement with frequency compression because the conventional processing condition was able to match targets to 4000 Hz. Participant comments made during the treatment phase included that of new audibility of warning signals at school and during use of personal listening devices; the participant viewed these new sounds in a positive manner. A significant withdrawal effect was measured for consonant recognition and detection of /s/.
relative to the final score for the treatment condition. No significant trends were observed within the treatment condition, suggesting limited acclimatization (see Table 2), although ceiling performance limited our ability to measure further change on many measures. Error pattern analyses (see the Appendix) revealed that this participant had initial difficulty identifying /s/ and /v/ sounds with frequency compression; /b–v/ recognition improved with acclimatization.

**Case Study 2**

Case Study 2 is an example of a child who received significant benefit from frequency compression in addition to nonlinear acclimatization trends but had initial decrement on some measures. Figure 4 displays all results for Case Study 2. Significant initial benefit with frequency compression was measured for the plural recognition task, whereas significant initial decrement was
measured for /s–>/ discrimination and />/ detection. Significant overall treatment benefit was found on the plural and consonant recognition tasks, whereas significant overall treatment decrement was found for the />/ detection task. Significant changes occurred when frequency compression was withdrawn, with poorer performance on /s–>/ discrimination and better performance on />/ detection. Acclimatization trends were observed for consonant recognition, /s–>/ discrimination- and detection-based tasks with significant nonlinear acclimatization trends for consonant recognition, and /s–>/ discrimination (see Table 2). Error pattern analyses (see the Appendix) suggest consonant confusions between affricate and fricative sounds; however, no clear patterns of error change can be observed across study conditions. Approximately

Table 2. Two-part analysis of acclimatization trends: Relative change in performance level, displayed in percent correct for speech recognition tasks and dB SPL for speech detection tasks, across cases.

<table>
<thead>
<tr>
<th>Case</th>
<th>Plural recognition</th>
<th>Consonant recognition</th>
<th>Discrimination</th>
<th>/s/ detection</th>
<th>/&gt;/ detection</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-3.30</td>
<td>-1.19</td>
<td>0.00</td>
<td>-1.00*</td>
<td>1.50</td>
</tr>
<tr>
<td>2</td>
<td>0.00</td>
<td>5.95*NL</td>
<td>12.04*NL</td>
<td>-1.00*</td>
<td>-0.50*</td>
</tr>
<tr>
<td>3</td>
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<td>4.76*NL</td>
<td>-5.56</td>
<td>-2.50*</td>
<td>-1.50*</td>
</tr>
<tr>
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<td>0.00</td>
<td>20.37*NL</td>
<td>-6.50*</td>
<td>-8.00*</td>
</tr>
<tr>
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<td>6.70*</td>
<td>8.33*</td>
<td>14.81*NL</td>
<td>5.00</td>
<td>2.00</td>
</tr>
<tr>
<td>6</td>
<td>6.65*</td>
<td>2.38*</td>
<td>1.85*</td>
<td>0.00</td>
<td>3.00</td>
</tr>
</tbody>
</table>

*Significant improvement over time. NLSignificant linear trend. **Significant nonlinear trend.

Figure 4. Case 2: Speech recognition, discrimination, and detection results displayed as a function of acclimatization time in weeks.
10 weeks with treatment was required to demonstrate significant consonant recognition improvement. One interesting aspect of this acclimatization pattern is the initial decrement observed with /s–ʃ/ discrimination, which resolved with increased experience with frequency compression.

Interpretation of this case is difficult given the mixed pattern of results. Electroacoustically, the 6300-Hz region of speech was audible with frequency compression but not without. Therefore, sounds with energy in this region (e.g., /s/) may have become audible, which would explain the improved performance in detection word-final plurality and in detection of /s/. However, for detection of an /ʃ/ sound and /s–ʃ/ discrimination, verification evidence suggests that audibility of the 4000-Hz region was present both with and without frequency compression. Therefore, the participant was required to change her discrimination of /s/ and /ʃ/ from a sound versus silence cue to those of newly audible cues. It appears that she did so following 8–10 weeks of experience with the new processor, but this came at the cost of poorer detection thresholds for /ʃ/. Looking at consonant recognition from a broader perspective, these various beneficial and unfavorable effects combined to provide an overall benefit to consonant recognition after 8–10 weeks of acclimatization to the new processor. The participant did not report any difficulty understanding speech over the course of the study. Overall, the results presented for Case 2 suggest more benefit than detriment with frequency compression.

**Case Study 3**

This case study describes a child who showed significant acclimatization post hearing aid fitting with frequency compression; however, a withdrawal effect was not measured for this participant. Figure 5 displays all results for Case 3. Significant initial benefit was measured for detection of /s/. Significant overall treatment benefit was measured for plural recognition and /s/ detection. When frequency compression was removed, no significant changes were measured. This may have been due to results approaching the significance level on the plurals task and to fairly small changes on /s/ detection overall. As well, performance on the discrimination task was at ceiling across all phases of the experiment. Error pattern analyses (see the Appendix) suggest that this participant experienced many different consonant identification errors over the course of the study; errors are not confined to specific distinctive features. However, acclimatization effects are noted for /r–ʃ/ and /r–ʃ/ confusions (i.e., identification improved over time) and on /z–dʒ/ confusions (i.e., more errors were made over time).

Within the treatment condition, significant acclimatization-related changes were measured for plural and consonant recognition and for detection tasks. A significant nonlinear trend was observed for plural recognition along with a linear trend for consonant recognition (see Table 2). Therefore, two different acclimatization trends are present in the data sets for Case Study 3; gradual improvement over time on the consonant recognition task and improvement after 6 weeks of acclimatization on the plural recognition task.

**Case Study 4**

The child in Case Study 4 had the largest degree of benefit from frequency compression in the study, along with prominent patterns of acclimatization. Prior to beginning testing, this child requested a significant amount of adjustments to the initial fitting due to loudness, which contributed to gain reduction at approximately 2000 Hz and above, consistent with reported fit-to-targets (see Table 1). TEN test results suggested the presence of cochlear dead regions at 2000 Hz and above; therefore, gain adjustments may have been driven by perceived distortion in sound quality and excessive loudness for sounds in the dead region (complaints related to average and loud conversational speech, spoken by school peers). These reports are consistent with those in the literature of listener-perceived sound quality at frequencies where dead regions are present (Moore, 2004). In addition to participant-driven gain reductions, we also created a noise management program (second to the main study worn listening program) to assist with hearing aid use in noisy environments; this program had the same frequency response as that of the testing program but included noise reduction digital signal processing.

Figure 6 displays all results for Case Study 4. Significant initial frequency compression benefit was measured for plural recognition. Significant overall frequency compression benefit was found on the plural recognition, /s–ʃ/ discrimination, and detection of /s/ and /ʃ/. Significant decrements occurred when frequency compression was withdrawn—on all measures except the consonant recognition task; therefore, withdrawal effects were measured for tasks where frequency compression benefit was also noted and for tasks measuring the effects of speech perception related to /s/ and /ʃ/ sounds. In addition, significant acclimatization trends were observed. A linear increase in performance with time was measured for plural recognition and detection based-tasks along with a nonlinear trend for /s–ʃ/ discrimination (see Table 2). Error pattern analyses (see the Appendix) suggest improved consonant identification with frequency compression for some of the affricate, fricative, and other consonant sounds. Specifically, identification of /d/ improved with initial activation of frequency compression, /ʃ–k/ confusion improved over time, and identification of /ʃ/ and /ð/ sounds improved with acclimatization time.
Two unique acclimatization trends are present in the data presented for Case Study 4: gradual improvement over time for plural recognition and detection-based tasks and improvement after a specific period of acclimatization (i.e., approximately 6 weeks) for the discrimination task. Given this participant’s history and extensive dead regions, enabling frequency compression likely would have provided novel sounds. For this reason, an acclimatization period may have allowed this listener to associate these novel cues with specific phonemes (to be able to recognize and discriminate sounds). The significant withdrawal effect reported across four out of the five tasks suggests that benefit change over time can be attributed to novel speech cues introduced with frequency compression as opposed to practice effects.

**Case Study 5**

Case Study 5 is an example of a child who received significant benefit after acclimatizing to frequency compression. Across measures, this child’s within-session variability was larger than that of other children, resulting in larger CIs. Figure 7 displays all results for Case 5. Significant initial and overall frequency compression benefit was measured for the discrimination task; a significant acclimatization effect occurred at approximately 8 weeks. Overall frequency compression decrement was measured for both detection tasks. When frequency compression was withdrawn, /s/ detection was significantly poorer. This participant did not comment on differences in sound quality or perceived speech perception ability.
over the course of the project. It is unclear why this participant experienced a performance decrement with frequency compression on the detection tasks. Hearing threshold levels, screened on more than one occasion, ruled out the presence of threshold shift.

Significant acclimatization-related improvement was measured in plural and consonant recognition as well as for /s–f/ discrimination (see Table 2). A large improvement in /s–f/ discrimination ability was observed after approximately 8 weeks. Error pattern analyses (see the Appendix) suggest an initial decrement in identifying /tʃ/ and /f/ sounds, with /f/ largely being confused with /s/. Initial improvement in /z–v/ identification with frequency compression is also noted. Over time, /tʃ/, /dʒ/, /s/, and /ð/ identification improved with frequency compression. Improvement in /s/ identification was largely due to less /s–f/ confusions over time. Withdrawing frequency compression resolved /s–f/ confusion but introduced greater difficulty identifying /d/.

**Case Study 6**

The child in Case Study 6 received little benefit from frequency compression and performed relatively poorly on all speech perception measures. Recall that this adolescent had the most hearing loss of all cases and was a long-standing wearer of monaural amplification due to lack of benefit amplification in her poorer ear. Although the
study aid provided greater range of sounds than was audible with her previous aid, speech audibility was very limited in the high frequencies. The chosen frequency compression setting was among the strongest available in the clinical software, yet neither the 4000-Hz bands nor the 6300-Hz bands were made audible (see Table 1). Aided measurements of /ʃ/ indicated that the lower shoulder of the /ʃ/ frication band was above threshold only when frequency compression was applied, whereas the /s/ frication band was well below threshold regardless of frequency compression activation/deactivation. Therefore, this case illustrates outcomes associated with a less-than-optimal fitting, even with frequency compression, due to limitations in fitting arising from profound hearing loss and device limitations.

Figure 8 displays all results for Case Study 6. Significant initial and postacclimatization frequency compression benefit was measured on the discrimination task. On the basis of the measurements of aided speech bands and aided live /ʃ/ and /s/, this may relate to hearing a partial cue for /ʃ/ and differentiating it from an inaudible or very soft /s/ when using frequency compression, versus hearing neither sound when frequency compression was not active. This type of discrimination was previously observed in studies of children with moderately severe to profound hearing losses (Kosky & Boothroyd, 2003). Within the first half versus last half of the treatment condition, we observed small but significant acclimatization-related improvements for plural identification, consonant recognition, and /s–ʃ/ discrimination (see Table 2). However,
the acclimatization trend across the treatment period did not reveal a significant linear or nonlinear pattern and was not accompanied by a significant withdrawal effect (this result pattern is detailed below in the Discussion section). Error pattern analyses (see the Appendix) are difficult to interpret for this participant, as they are scattered across many different consonants and are nonuniform; this is thought to be due, in part, to the degree of hearing loss presented in Case Study 6. Initial improvement in identification of /b/ is noted with frequency compression, and greater /r–w/ confusions are noted over the treatment condition. Overall, this adolescent experienced significant frequency compression benefit in /s–ʃ/ discrimination. The small but significant acclimatization-related improvements experienced during a trial with frequency compression were not large enough to result in significant benefits when compared to baseline or posttrial testing without frequency compression.

**Discussion**

In this experiment, we evaluated treatment effectiveness and auditory acclimatization effects attributable to frequency compression hearing aid signal processing. Performance with frequency compression varied across speech perception measures and participants. In general, a unique pattern of results was measured for each participant, with some participants demonstrating large changes in speech perception ability with frequency compression.
Auditory Acclimatization and Treatment Effectiveness

Fricative sounds (i.e., using /s/ and /ʃ/) effects were measured through the use of high-frequency fricative sounds. One participant (Case Study 3) did not demonstrate posttrial changes on any measure, and his performance was generally at ceiling across measures and processors. Frequency compression benefit, when it occurred, had a magnitude of up to 20% for tasks scored in percentage and up to 10 dB for aided thresholds. A frequency compression decrement of 12 dB was measured for one participant, even when the same participant derived benefit in other measures. We investigated acclimatization effects over 4 months in older children and adolescents in an effort to minimize maturational effects; however, improvements measured over time could have been due, in part, to maturation.

Treatment Effectiveness

Treatment effects described by outcome measure can be summarized as follows. For the plural recognition task, frequency compression benefit was measured for three participants: For one participant, benefit was measured right away, another demonstrated benefit only after an acclimatization period, and the third demonstrated an initial improvement in plural recognition that further improved with acclimatization time. For the consonant recognition task, none of the participants demonstrated initial benefit with frequency compression hearing aids; overall or posttrial benefit was measured for two of the participants. Benefit was measured on the /s–ʃ/ discrimination task for three of the participants, with all three demonstrating overall benefit and two demonstrating initial and/or posttrial benefit; initial/posttrial performance decrement was measured for one participant on this task. Finally, on the detection tasks, benefit on either the /s/ or /ʃ/ task was measured initially and/or posttrial for five of the six participants, with slightly more participants demonstrating improved /s/ detection ability when compared with /ʃ/ detection; an initial performance decrement, resulting in posttrial benefit, was measured for one participant on the /ʃ/ detection task. Overall, these results may indicate that detection measures appear to require less acclimatization time to show treatment effectiveness compared with discrimination or recognition measures. Further research would be required to evaluate this speculation.

Auditory Acclimatization

For two participants (Case Studies 2 and 4), postacclimatization benefit from frequency compression was accompanied by significant improvements over the treatment interval, suggesting that a period of acclimatization was needed for these listeners to benefit from the processor. These same participants did not show improvements during their baseline trial without frequency compression, suggesting that benefit observed over time was specific to audibility changes from frequency compression rather than from new sound from the study aids versus their previous fittings.

Frequency compression–related decrement was most apparent for the child with the flattest audiometric configuration (Case Study 2). Results suggest that the child in Case Study 2 had more difficulty detecting /ʃ/ and discriminating /ʃ/ from /s/ when frequency compression was activated. Although this participant learned to differentiate between /s/ and /ʃ/ and demonstrated improved consonant discrimination and error patterns, her ability to identify /ʃ/ was best without frequency compression. We cannot fully explain this pattern of results, which speaks to the fact that frequency compression may introduce adverse speech perception effects for some listeners. A different setting may have resulted in different outcomes, but investigation of performance with an alternative frequency compression setting was beyond the scope of this study.

Two unique acclimatization patterns were measured in this study: gradual improvement over time (i.e., a linear trend) and improvement after a specific period of acclimatization (i.e., a nonlinear trend). The latter pattern, resembling an S-shaped curve, mainly occurred for the /s–ʃ/ discrimination task (Case Studies 2, 4, and 5). An S-shaped pattern may be associated with the nature of the discrimination task and/or the novel cues presented with frequency compression. Specifically, this task requires the participant to be able to not only detect novel sounds but also differentiate between them. In some cases, only one sound may have been novel to the participant (e.g., new audibility of /s/ only), and the amount of frequency shifting may have differed for /s/ versus /ʃ/. Differentiating between /s/ and /ʃ/ in the presence of high-frequency hearing loss may be more difficult when the previously learned cues (e.g., the frequency location of a frication band) have been frequency lowered. This type of change likely requires the listener to relearn cues associated with a specific phoneme. The literature suggests brain plasticity as a possible underlying mechanism for auditory acclimatization (Palmer, Nelson, & Lindley, 1998; Willott, 1996); the literature also suggests that frequency discrimination tasks are highly amenable to auditory learning effects that generalize across tasks (Wright & Zhang, 2009). Because the peak frequency is an important cue for fricative recognition (Dubno & Levitt, 1981), we may speculate that learning the new frequency locations of /s/ and /ʃ/ may be required for some users of frequency-lowering strategies. Brain plasticity may be
required to excel on such a task, requiring the listener to learn to represent and integrate new acoustic information. Furthermore, some participants with S-shaped data patterns for the discrimination task required 6–10 weeks of acclimatization time prior to measurement of significant frequency compression benefit. In other cases (e.g., Case Study 6), participants demonstrated significant initial benefit, which remained stable over the treatment phase.

We also noted other interesting acclimatization results. In some cases, participants scored more poorly on some measures with conventional processing following the frequency compression trial (even though they did not benefit from frequency compression) versus the baseline trial. A possible explanation includes perceptual adjustment to speech cues, to the point that listening without frequency compression was disadvantageous. In other cases, significant improvements measured during treatment with frequency compression were followed by equally good scores with frequency compression withdrawn. A possible explanation for absent withdrawal effects may be a carryover effect in which the participants learned to use cues during the treatment phase of the study and were able to apply this learning even without the frequency-compressed signal (i.e., in the withdrawal phase). One possible mechanism for a carryover effect could be neural reorganization. Alternatively, it could be that the increased bandwidth of the study aids (versus their own aids) caused an acclimatization effect that was not specific to frequency compression. Although we took multiple measures during the baseline trial to guard against this confound, it is not possible to entirely rule out the potential for further acclimatization to conventional processing beyond the baseline phase in all cases.

**Test Battery and Trial Length**

The test battery used in this study was chosen to be sensitive to the effects of frequency-lowering hearing aids, both for high-frequency sounds and across a wide range of consonants. Stimuli containing fricative sounds such as /s/ and /ʃ/ were of particular interest in this study because both contain high-frequency energy and because the nonlinear nature of the frequency compressor used here provides more lowering for /s/ than for /ʃ/, leading to the possibility of overlap of the two fricatives. The test battery contains stimuli spoken by different speakers, which resulted in minor spectral differences across tasks (see Figures 1 and 2), and spectral stimuli that are consistent with those reported in the literature (Boothroyd & Medwetsky, 1992; Pittman et al., 2003). The use of frequency compression processing alters the spectral shape of individual fricatives by lowering and narrowing the frication band. This depends on how the frequency compression was set; stronger settings provided more lowering effects. It is possible that frequency compression can alter the nature of fricatives substantially, resulting in their being perceived as a different phoneme or perhaps as a nonrecognizable sound. Certainly, some such effects were noticed in the consonant confusion matrices. These effects arose from a task in which listeners used a closed-set response and were, therefore, forced to designate a phonemic response. Results from the consonant recognition test suggest that the participants experienced many different speech sound confusions in addition to the hypothesized /s–ʃ/ confusion. Other types of confusions noted in this study include, but were not limited to, /ð–v/, /r–w/, /s–ʃ/, and /tʃ–k/. Some consonant confusion errors were present in the baseline fitting, some were a result of the introduction of frequency compression, and some resolved over time. We did not evaluate whether listeners would misidentify some phonemes if they had been given an open-set task, although this would be an interesting question for further research. Other factors to consider in test battery construction include the use of adaptive measures. One participant in this study performed at ceiling on all measures but /s/ detection, which was not only an adaptive task but also the highest frequency stimulus and was, therefore, highly sensitive to the effects of frequency lowering. These ceiling effects were not anticipated. The tasks themselves are difficult either due to the high-frequency content of the stimuli in combination with participants’ hearing losses (discrimination and detection measures), low presentation level (plurals task), or low context (consonant recognition). Factors explaining the higher-than-anticipated scores may include the older ages of these adolescent participants—although many adolescents were tested on similar tasks by Glista et al. (2009)—or more recently developed hearing technologies that include broader bandwidth in both processing and output than the aids used by Glista et al. Ceiling performance with frequency compression hearing aids was reported previously (Wolfe et al., 2011).

**Comparison With Other Studies of Frequency Lowering**

Certain findings reported in the present study differ from those previously reported. Simpson and colleagues (2006) investigated frequency compression outcomes in seven adult participants with steeply sloping losses. The participants in the Simpson et al. study did not receive frequency compression benefit after a brief or absent acclimatization period. The authors of that study concluded that frequency compression for steep slopes may use a strong degree of frequency lowering and that, perhaps, this may require additional adaptation time.
and/or training efforts (Simpson et al., 2006). In the present study, we found evidence to support this speculation in some (but not all) listeners; however, due to the small number of participants included in this study, further research is needed to investigate this correlation. A longer acclimatization period was needed to achieve significant frequency-lowered benefit for recognition tasks when compared with detection tasks; these findings are consistent with those reported in studies of children by Auriermoom et al. (2009) and Wolfe et al. (2011). Similarly, in a study including adult listeners, Kuk, Keenan, Korhonen, and Lau (2009) discussed the need for an adaptation period with frequency-lowering hearing aid technology, given the possibility that some wearers may not immediately accept the sound quality of such devices. Factors that may explain differences between the results reported in this study and those reported by Simpson et al. include the use of pediatric participants, more recently developed hearing instruments, and the use of a different fitting method. Further research would be required to determine the individual role of each of these factors.

In a previous study on frequency transposition, error pattern analyses revealed improved identification for some consonants, in addition to the introduction of different confusions (Robinson et al., 2007, 2009). Specifically, errors confusing /s/ with /f/ increased with the introduction of frequency lowering; New confusions remained despite a 5-week period of experience with the study hearing aids. Robinson and colleagues (2009) speculated that the lack of overall benefit measured with frequency lowering may have related, in part, to the relatively short trial period. Alternatively, findings from the current study suggest that speech sound confusions introduced with frequency lowering may resolve over time, for some listeners, and with a prolonged acclimatization period. It is difficult to compare these two studies directly, given the difference in fittings methods, participant ages, and processing schemes evaluated. Further research is needed to directly compare outcomes with different forms of frequency-lowering technologies.

In summary, this experiment provided case-specific evidence of auditory acclimatization to newly audible high-frequency sounds for some of the child listeners (ages 11–18 years) and in the presence of a well-controlled adaptation period. A unique pattern of results was measured across cases, suggesting that treatment and/or acclimatization effects measured within this study cannot be generalized outside of case-specific findings. Given the low incidence of permanent childhood hearing loss and the lower incidence of precipitous hearing losses within this group, the study of acclimatization effects through the use of strategies such as single-subject design allowed a systematic exploration of outcome in this group. Because the exact limits of candidacy for frequency lowering are not yet known, we sampled across a range of high-frequency hearing losses. In this sample, we had some participants who received little or no benefit from this technology and others who received significant benefit that sometimes required a period of acclimatization in order to take effect. These results are consistent with those of Glista et al. (2009), who reported a significant association between the degree and configuration of high-frequency hearing loss and candidacy for frequency compression, as well as those of Wolfe et al. (2011), who reported improvement of frequency compression benefit over time. In the present study, we measured the time course of acclimatization (when it did occur) by sampling outcomes at frequent intervals. From this design, we observe that acclimatization trends (when they occur) take two forms: (a) gradual linear changes and (b) sudden nonlinear changes that occur after a period of 6–10 weeks. Presence or absence of speech perception change varied not only across people but also across outcome measures. On the basis of this, we concluded (a) that individual determination of candidacy, fitted settings, and outcomes of frequency compression are warranted in clinical practice and (b) that further research is required to determine limits of candidacy and an optimal test battery for use in evaluation of outcome. Furthermore, research is needed with new frequency-lowering strategies to determine optimal methods for fitting, particularly in cases of asymmetrical hearing losses, the construction of optimal outcome batteries, and evaluations of whether participant variables such as developmental status and hearing-loss profile affect benefit and/or acclimatization.

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References


**Appendix** (p. 1 of 2). Error pattern analyses across participants.
Appendix (p. 2 of 2). Error pattern analyses across participants.

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