Influence of aided audibility on speech recognition performance with frequency composition for children and adults

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Acronyms and Abbreviations: DSL= desired sensation level; HA = hearing aid; NFC = nonlinear frequency compression; FC = frequency composition; MAOF = maximum audible output frequency; SII = speech intelligibility index; SNR = signal-to-noise ratio; SPL = sound pressure level; WDRC = wide-dynamic range compression

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ABSTRACT

Objective
The primary purpose of this project was to evaluate the influence of speech audibility on speech recognition with frequency composition, a frequency-lowering algorithm used in hearing aids.

Design
Participants were tested to determine word and sentence recognition thresholds in background noise, with and without frequency composition. The audibility of speech was quantified using the speech intelligibility index (SII).

Study Sample
Participants included 17 children (ages 6-16) and 21 adults (ages 19 to 72) with bilateral mild-to-severe sensorineural hearing loss.

Results
Word and sentence recognition thresholds did not change significantly with frequency composition. Participants with better aided speech audibility had better speech recognition in noise, regardless of processing condition, than those with poorer aided audibility. For the child participants, changes in the word recognition threshold between processing conditions were predictable from aided speech audibility. However, this relationship depended strongly on one participant with a low SII and otherwise, changes in speech recognition between frequency composition off and on were not predicable from aided speech audibility.

Conclusion
While these results suggest that children who have a low-aided SII may benefit from frequency composition, further data are needed to generalize these findings to a greater number of participants and variety of stimuli.

INTRODUCTION

Listeners with sensorineural hearing loss experience limited access to high-frequency speech sounds using conventional hearing aid processing due to limitations of the hearing aid (HA) receiver bandwidth and the listener's degree of hearing loss (Kimlinger et al., 2015). Limited high-frequency bandwidth through conventional amplification may adversely affect speech recognition compared to extended bandwidth conditions (Hogan & Turner, 1998; Ricketts et al., 2008), with some studies finding equivalent speech recognition, or, for some individuals, poorer speech recognition with a wider bandwidth (Baer, et al., 2002; Ching, et al., 1998). Limited bandwidth in HAs led to the development of frequency-lowering algorithms designed to increase bandwidth by shifting inaudible high-frequency speech sounds into lower, audible-frequency regions. The goal of these strategies is to maximize the frequency range that is audible to the listener while limiting potential detrimental effects of distortion and reduction in the listener's ability to resolve differences across frequency (Scollie et al., 2016; Souza et al., 2013). Recent effort has focused on identifying those patients that benefit from frequency lowering—such was the purpose of this experiment.

Frequency-lowering algorithms

Three examples of frequency-lowering algorithms used in hearing aids include nonlinear frequency compression (NFC), linear frequency transposition (LFT), and frequency composition (FC). With NFC, the input bandwidth above a specified start frequency (source region) is compressed into a narrower bandwidth (destination region) as determined by the compression ratio (Simpson et al., 2005). With LFT, the peak in the spectrum above the start frequency is identified, lowered and band-pass filtered by one octave, amplified and added to the sounds in the destination region (Kuk et al., 2009). This study focused on FC, a frequency-lowering algorithm in which two or three source regions are recoded into a single destination region at a lower frequency. The lowered information from the source regions is superimposed on the extant energy in the destination region (Angelo et al., 2015; Salorio-Corbetto et al., 2017). The source regions are placed in the destination region at a default level that is 3 dB less than the signals that originate in those regions—however this level can be modified. The high-frequency components in the source regions are also preserved (see Figure 1).

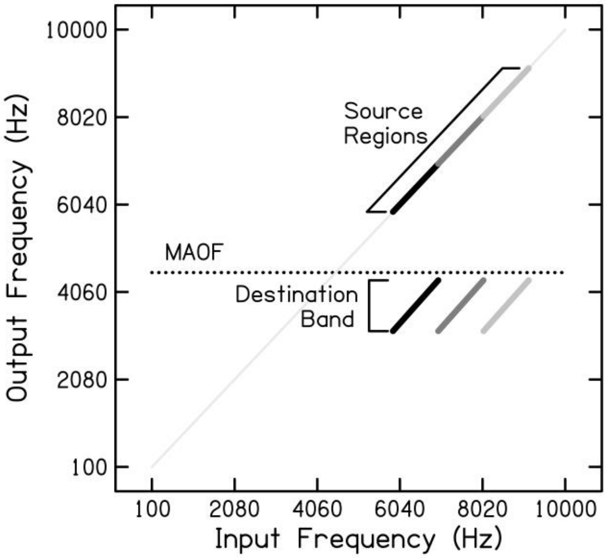


Figure 1. An input-output function showing how frequency composition compresses and superimposes three high-frequency source regions (black, dark gray, and light gray) into a single destination band. In this example, the destination band is below the maximum audible output frequency (MAOF). The MAOF is the highest frequency for which speech is equal to or greater than the threshold of hearing. The high-frequency components in the source regions and above are also preserved.

Role of audibility, masking, age, and stimuli on perception with frequency lowering

Two studies to date examined the impact of FC on speech recognition by comparing speech recognition, for a variety of speech stimuli, with and without FC (Kirby et al., 2017; Salorio-Corbetto et al., 2017). Both studies included an acclimatization period of hearing aid use 6 to 8 weeks prior to speech testing. Participants included children and adults. Neither study found a benefit in speech recognition; however, Salorio-Corbetto et al. (2017) observed improved word-final detection of /s/ and /z/. Subjective ratings by the participants in Salorio-Corbetto et al. did not differ between FC on and off, whereas some of the participants in Kirby et al. indicated a significant preference for the intelligibility of speech with FC. Kirby et al. also obtained, using a dual-task paradigm, measures of listening effort. Listening effort did not differ between FC on and off. Thus, data to date do not show positive or negative effects of FC processing for speech recognition. However, considerable variability in benefit from FC has been documented, suggesting that some listeners might benefit from usage of FC.

Audibility, masking, age, and stimuli are four reasons that might explain why some participants do not appear to benefit from the provision of FC. Work with NFC has demonstrated that speech recognition with frequency lowering is improved when audibility is increased. Specifically, McCreery and colleagues (2013, 2014) observed a systematic relationship of the improvement in audibility with NFC to the improvement in speech recognition that occurred. Other studies that documented changes in audibility with NFC (Glista et al., 2009; Wolfe et al., 2010) also found improvements in word recognition; however, a subset of participants did not have improved speech recognition even when the audibility of speech in the high frequencies was increased (Glista et al., 2009; Hillock-Dunn et al., 2014; McCreery et al., 2014). There is disagreement about the relationship of hearing loss to benefit from NFC. Some work has reported that participants with greater hearing loss experience a larger benefit (e.g. Souza et al., 2013). Kirby et al. (2017) asserted that FC benefit might be limited to those with more severe hearing loss (i.e. less audibility) and, consistent with that notion, Angelo et al. (2015) observed an overall benefit of FC for a group of participants with greater hearing loss than the participants in Kirby et al. (2017). However, one study instead found that participants with less hearing loss can benefit more from NFC than those with greater hearing loss (Brennan et al., 2017), possibly because listeners with greater audibility are better able to extract the lowered information (due to a less damaged auditory system) and because of less lowering (distortion). Although both Kirby et al. (2017) and Salorio-Corbetto et al. (2017) selected destination regions where the lowered sounds could be made audible for each participant, the influence of audibility on benefit was not directly examined.

Masking could occur with FC due to mixing of the sounds in the destination region with that in the source region. This masking could limit the ability of the listener to extract the information from the sounds now located in the destination region. Consistent with this idea, benefits in speech recognition have been observed for NFC, which is a frequency-lowering algorithm that does not overlap sounds from the destination region with that of the source region (Brennan et al., 2017; Glista et al., 2009; McCreery et al., 2013; McCreery et al., 2014; Wolfe et al., 2010). In contrast, benefits in speech recognition have not been observed for those frequency-lowering algorithms (FC, LFT) that mix sounds from the destination region with that of the source region (Kirby et al., 2017; Miller et al., 2016; Robinson et al., 2007; Robinson et al., 2009; Salorio-Corbetto et al., 2017, 2019). It should be noted that when measured across multiple visits, Auriemmo et al. (2009) and Kuk et al. (2009) observed improvements in vowel and consonant recognition with LFT. However, because the processing condition was not counter balanced across visits, the improved speech recognition observed may have been due to test learning instead of due to improvements in audibility provided by LFT. Due to the lack of a control group, it is impossible to assess whether the improvements observed in these studies were related to LFT or to practice effects on the speech recognition task.

Even with the provision of amplification, children with hearing loss typically demonstrate delayed language development (Tomblin et al. 2015) and recognize fewer words than children with normal hearing (Brennan et al., 2016; McCreery et al., 2015, 2019). Consequently, finding more effective treatment options that ameliorate the reduced audibility of speech for children with hearing loss is a necessary step toward improving their outcomes. Studies have examined child to adult difference in benefit from frequency lowering. Factors that may impact FC benefit for children relative to adults include children being prescribed greater audibility than adults (e.g. Scollie et al., 2005)—resulting in less need for frequency lowering for the same degree of hearing loss—and also potentially greater reliance on acoustic cues due to on-going development of high-order cognitive skills that facilitate speech recognition (McCreery et al., 2019). While Glista et al. (2009) observed a greater benefit of NFC for their child than adult participants, others have observed a similar benefit for both age groups (Brennan et al., 2017; McCreery et al., 2014). Kirby et al. (2017) examined FC for child and adult participants and observed no effect of age group for monosyllabic words, low-context sentences (e.g. He puts the cats through the dream), or consonant-vowel-consonant stimuli; however, the adults (but not children) rated speech intelligibility as better with FC.

The availability of contextual information embedded may impact the benefit observed with frequency lowering. While both adults and children correctly recognize fewer words when high-frequency information is removed with low-pass filtering, the steepness of this decline is greater for stimuli with less linguistic information (Spratford, et al., 2017). Consequently, a greater benefit of frequency lowering is more likely to occur for stimuli with less linguistic information. The findings of a meta-analysis by Simpson et al. (2018) were consistent with this notion—NFC significantly improved the recognition of consonants embedded in nonsense words, but not word recognition in quiet or sentence recognition in noise. While previous work with FC has used a variety of speech stimuli, including consonants embedded within nonsense syllables (i.e. vowel-consonant-vowel), word-final /s/ and /z/ detection, monosyllabic words, and sentences embedded in background noise (Kirby et al., 2017; Salorio-Corbetto et al., 2017), this experiment expands on that previous work with FC by using a recently developed list of words and low-context sentences (Spratford et al., 2017).

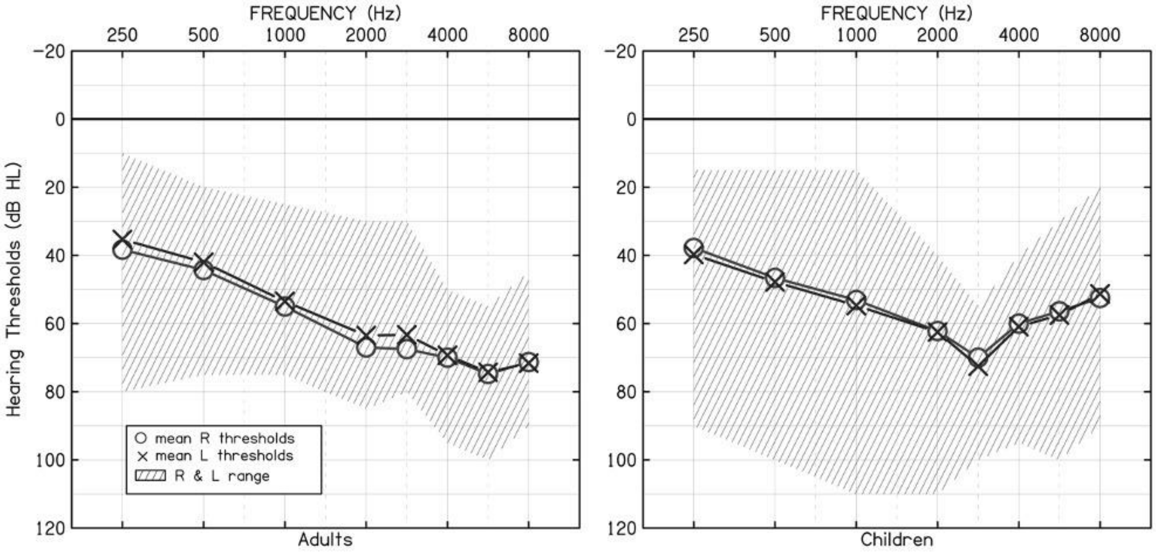
Specifically, this experiment was designed to test the following primary research question: does aided audibility predict individual benefit in speech recognition with FC? This question was answered by obtaining estimates of the signal-to-noise ratio required for 50% correct recognition (SNR50) of words and sentences in noise, with and without FC, using a hearing-aid simulator. We used low-context stimuli as an attempt to isolate acoustic effects. Participants were children and adults with mild-to-severe degrees of hearing loss. We predicted that individuals with less aided audibility would show larger improvements in SNR50 with FC compared to participants with greater audibility. Due to greater reliance on acoustic cues, we also predicted a larger benefit of FC for the child than adult participants and for the word than low-context sentence stimuli.

MATERIALS AND METHODS

Participants

Participants included 17 children (ages 6-16 years, mean age = 11.9) and 21 adults (ages 19 to 72 years, mean age = 43.6) with mild-to-severe sensorineural hearing loss (see Figure 2). All of the participants owned binaural hearing aids. The number of participants was based on the assumption of similar observed effects to that of McCreery et al. (2013). Adult participants reported wearing their HAs 9.2 hours per day on average (range: 0 to 17.0 hours). Children wore their devices an average of 11.8 hours per day (range: 0 to 17.0 hours) based on self- or parent-report. Six of the adults and three of the children were using frequency-lowering technology in their personal HAs on the day of testing, verified in the manufacturers' programming software. Participant recruitment and testing was approved by the Boys Town National Research Hospital Institutional Review Board. Participants were paid $15 per hour for their participation. Children could also select a book to take home.

Figure 2. Mean hearing thresholds for right ear (O) and left ear (X) for adults (left panel) and children (right panel). The range of thresholds across frequency for each age group is plotted as the hatched area. *R* = right ear; *L* = left ear.



Word and Sentence Stimuli

One hundred and thirty-eight monosyllabic words with and without the plural morpheme /s/ and two hundred and sixteen singular and plural nouns embedded in low-context sentences were used to assess speech recognition. These stimuli were described by Spratford et al. (2017) and were spoken by a 22-year-old female research assistant with a standard midwestern dialect. Example sentences include (emphasis on target word) "they sweep the *soap* under the table" and "he rakes the *ducks* across the field". Target words were within the average lexicon for the youngest child participating in the study (Storkel & Hoover, 2010). Three lists of words and three lists of sentences were created and balanced by initial phoneme of the target word. Half of the targets in each word and sentence list contained the plural morpheme /s/. For the inflected words, there were equal numbers—across the three lists—of voiced and voiceless markers (/z/ and /s/, respectively). Low-context sentences were created so that the presence or absence of the plural morpheme was not predictable based on lexical content. Gaussian noise that was frequency shaped using 1/3 octave-band filters to the long-term average spectrum of the speech stimuli was used as background noise.

Instrumentation

The measures of speech recognition were presented using custom software (MATLAB, The MathWorks, Natick, MA) on a personal computer with a MOTU UltraLite-mk3 Hybrid sound card (Mark of the Unicorn, Cambridge, MA). Stimuli were routed through a PreSonus HP4 headphone amplifier (PreSonus Audio Electronics, Baton Rouge, LA) and then through a pair of Sennheiser HD-25-1 II headphones (Sennheiser Electronic Corporation, Old Lyme, CT).

Hearing Aid Simulation and Aided Speech Intelligibility Index

The HA simulator consisted of an FC circuit, 8-channel filterbank, wide-dynamic range compression (WDRC), and output-limiting compression. A MATLAB program, with a 22.05 kHz sampling rate, described by McCreery et al. (2013, 2014) was used to provide amplification. Output levels, kneepoints, and compression ratios were set to Desired Sensation Level (DSL) v5.0a prescriptive targets (Scollie et al., 2005) with FC off, and the same settings were used for FC on. Note that the DSL v5.0 child algorithm prescribes more gain than the adult algorithm. Children were prescribed the DSL-child algorithm while adults were prescribed the DSL-adult algorithm. Attack and release times for the WDRC circuit were 5 and 50 ms (ANSI, 2009) for each of the eight channels with center frequencies of 0.315, 0.5, 0.8, 1.25, 2, 3.15, 5, and 8 kHz. The input signal level and compression ratio determined the WDRC output above the kneepoint as well as the output-limiting compression kneepoint.

When signal level was above the output-limiting compression kneepoint, the compression ratio was 10:1 with 1- and 50-ms attack and release times, respectively. When signal level was below the WDRC kneepoint, linear amplification was provided. Following the WDRC stage, signals were summed across channels and submitted to an output-compression circuit with 105 dB SPL kneepoint and 10:1 compression ratio. Stimuli were processed with FC off or with FC on. For the FC on conditions, stimuli were frequency composed before the WDRC circuit. Since HAs employing FC were not commercially available from Oticon at the time of this study, a MATLAB program—provided by the manufacturer—was used to implement FC processing.

For each participant, output levels for a 60 dB SPL speech passage representing the long-term average speech spectrum (Byrne et al., 1994) were estimated in a Knowles Electronic Manikin for Acoustic Research (KEMAR) with an IEC 711 coupler (G.R.A.S. Sound & Vibrations, Holte, Denmark) and set to within 5 dB SPL of the DSL targets. The 13-second speech passage consisted of a male talker discussing carrots and was obtained from the Verifit electroacoustic measurement system (Audioscan, Dorchester, Ontario, Canada). The maximum audible output frequency (MAOF) for each subject and processing condition was estimated based on the highest frequency where the aided long-term average speech spectrum intersected each subject's thresholds in dB SPL. For adults the average MAOF with FC off was 5047 Hz (range: 1500 to 8000 Hz). For children the average MAOF with FC off was 6703 Hz (range: 750 to 8000 Hz). The MAOF was then used to select the FC setting, as described in the following section.

Using the output levels for the 60 dB SPL long-term average speech spectrum, audibility with the hearing aid simulator was quantified with the Speech Intelligibility Index (ANSI, 1997). Using a transform factor, participant thresholds were converted to dB SPL in KEMAR, linearly extrapolated to the center frequencies for one-third octave filters, adjusted to account for the internal noise spectrum and transformed to one-third octave band levels (ANSI, 1997, 2004; Pavlovic, 1987). The aided speech intelligibility index (SII) was then calculated using the ANSI one-third octave band procedure with the standard band importance function.

Frequency Composition Settings

Each participant was tested with one FC setting, chosen from five possible FC settings that varied by source and destination frequency regions (see Table 1). The FC setting was chosen for each participant using a modified protocol for fitting NFC (Hillock-Dunn et al., 2014). The FC setting selected was the highest FC setting that resulted in the MAOF being above the maximum frequency of the destination region. For example, if the MAOF was 4500 Hz the medium FC setting was chosen since the highest frequency of the destination region was 4125 Hz and choosing a higher FC setting would have resulted in portions of the destination band being above MAOF. The destination signal level was set to the default value (3 dB less than the signals from the destination region).

Table 1. Five FC settings varying by source and destination frequency regions. *n* = number of subjects with that FC setting.

FC Setting	Source Region (Hz)	Destination Region (Hz)
Low (*n*=4)	3875-6500	1875-2500
Medium-Low (*n*=6)	5125-8365	2625-3365
Medium (*n*=5)	5875-9125	3375-4125
Medium-High (*n*=4)	6472-9444	4250-5000
High (*n*=19)	6475-9775	5225-6026

The same FC setting was selected for both ears of each participant. Three adults and one child had significant asymmetries in audiometric thresholds, and in these cases the FC setting for the better hearing ear was selected for both ears. The MAOF for FC off was at or above 8000 Hz for 18 of the 38 participants. This high MAOF was likely due to the use of headphone transducers with a greater output capability than what can be produced with HA receivers. For these participants, the maximum audible input frequency with FC on was 9775 Hz, for an increase of 1775 Hz. For the remaining participants, the distribution of FC settings was similar between the lower settings and the increase in the maximum audible input frequency ranged from 3444 Hz to 5000 Hz. The maximum audible input frequency with FC on was estimated using the Speech Rescue Fitting Assistant v1.0 (https://web.ics.purdue.edu/~alexan14/fittingassistants.html).

Procedures

All of the procedures were completed in a sound-treated audiometric test room. Pure-tone audiometric thresholds were obtained using ER-3A insert earphones (Etymotic Research, Inc., Elk Grove Village, IL) if an audiogram within 6 months of visit was not on file. Audiometric thresholds were tested following ASHA (2005) guidelines for manual pure-tone threshold audiometry at octave frequencies .25 to 8 kHz, inter-octave frequency .6 kHz, and remaining inter-octave frequencies when there was a 20-dB threshold difference or more between two successive octave frequencies. After that, SNR50 was measured using the hearing aid simulator under headphones with FC on and off. Participants were seated at a table and were instructed that they would hear words and sentences and to repeat what they heard. If unsure, participants were encouraged to guess. Participants first completed a practice list of 21 sentences with the settings of the first FC condition applied. FC condition order was counterbalanced across participants using a Latin square design. List number and the presentation order of the stimuli within each list were randomized. Two lists, one word list and one sentence list, were selected for each FC condition. While sitting in the room with the participant, the examiner scored target words online as correct or incorrect on a computer.

An adaptive one-up, one-down staircase procedure was used to find the signal-to-noise ratio (SNR) giving 50% correct recognition on the performance-intensity function (Levitt, 1971). Target stimuli were presented at 60 dB SPL and the level of speech-shaped noise masker either increased or decreased based on the correctness of the repetition of the target word. The beginning SNR was 20 dB with initial adaptive step sizes of 18, 9, and then 6 dB. The remaining step size was 3 dB SNR until the track terminated after obtaining a total of seven reversals. Each participant completed two interleaved tracks at the same time, and unique words and sentences were presented from each list for each condition. The 50% threshold (SNR50) for each track was calculated by averaging the SNRs of the last four reversals, and the final threshold was determined by averaging those two threshold estimates.

Statistical Analyses

To examine the relationship between variables, the bivariate correlations among the dependent and independent variables were analyzed. To analyze mean differences in SNR50 by stimulus (words, sentences), processing condition (FC off, FC on), and age group (children, adults), a linear mixed model with random intercepts for each subject was conducted. The linear mixed model also included better-ear aided SII as a predictor variable. Linear mixed models allow for comparison of mean differences across repeated measures and conditions, continuous predictor variables, and their interactions. Using histogram and Q-Q plots, model residuals were inspected for normality and influential cases were identified using Cook's distance (Field, 2012). Statistical modeling was completed using MATLAB 2019b with the fitlme command. Due to a data collection error, SNR50 was not measured for sentences with FC on for one of the child participants. Therefore, this participant's data was excluded from the analyses.

RESULTS

The bivariate correlations among the dependent and independent variables are shown in Table 2. While aided SII was similar for the child and adult participants, participants with a higher aided SII tended to have a lower (better) SNR50 threshold. There were also significant correlations among the speech-recognition variables.

Table 2. Bivariate correlations (*r*) of predictor variables. * = $p < 0.05$, ** $p < 0.01$, and *** = $p < 0.001$. *Bold = p < .05. SII* = speech intelligibility index; *FC* = frequency composition; *SNR50* = signal-to-noise ratio at 50% correct.

	Age Group	Aided SII	SNR50 Words FC Off	SNR50 Words FC On	SNR50 Sentences FC Off
Aided SII	-0.05				
SNR50 Words FC Off	0.27	**-0.52****			
SNR50 Words FC On	0.29	**-0.58*****	**0.82*****		
SNR50 Sentences FC Off	0.17	**-0.52*****	**0.83*****	**0.80*****	
SNR50 Sentences FC On	0.32	**-0.47****	**0.76*****	**0.76*****	**0.73*****

Figure 3. The SNR50 for each processing condition (FC off, FC on) and stimulus (word, sentence) for adults (left panel) and children (right panel). *FC* = Frequency composition; *SNR50* = signal to noise ratio at 50% correct.

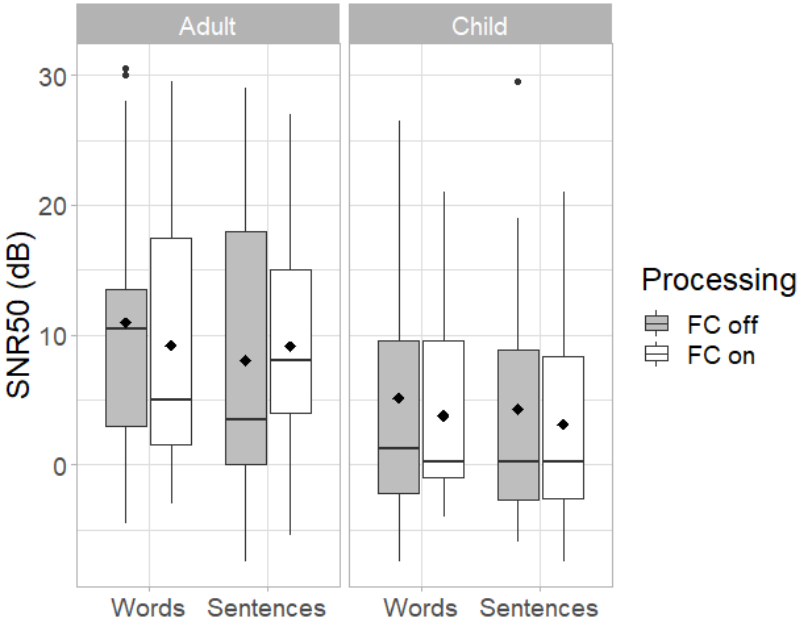


Figure 3 displays SNR50 for the word and sentence stimuli for each age group and condition and Table 3 shows the results of the linear mixed model. The model residuals were consistent with a normal distribution and their variance was evenly distributed with aided SII and the fitted model. The effect of processing was not significant with a 0.75 dB lower SNR50 with FC on than with FC off. There was a significant interaction of FC processing condition with age group (*p*=.049) and also a significant three-way interaction of FC-processing condition, age group, and stimulus condition (*p*=.028), however, the source of these significant interactions were unclear—none of the post-hoc t-tests, comparing FC on to FC off, were significant (children words: *t*=1.2, *df*=15, *p*=0.263; children sentences; *t*=0.8, *df*=15, *p*=0.450; adults words: *t*=1.1, *df*=20, *p*=0.281; adults sentences: *t*=-0.6, *df*=20, *p*=0.582).

Individual performance (SNR50) as a function of aided SII and FC condition are plotted—for each age group and stimulus condition—in Figure 4. Participants with higher aided SII had a significantly lower SNR50 (*p*<.001), with a model estimated 11 dB decrease in SNR50 per each 10-percentage point increment in aided SII. However, there was a significant three-way interaction of age group, FC-processing condition, and aided SII (*p*=.046) and also a significant four-way interaction of age group, FC-processing condition, stimulus condition, and aided SII (*p*=.022). The significant 3-way interaction must be considered within the context of the significant four-way interaction. The four-way interaction is illustrated in Figure 5, which plots FC benefit for both individual SNR50 thresholds and model estimated performance; the bivariate correlations of FC benefit with aided SII are also provided. For the word condition, child participants with a lower aided SII tended to perform better with FC on (*p*=.035). A similar, but not statistically significant, pattern occurred for the sentence condition with the adult participants. None of the correlations for the remaining conditions were significant.

Table 3. Linear mixed model for SNR50. Akaike information criterion = 989 and adjusted r-squared = .81. * = $p < 0.05$, ** $p < 0.01$, and *** = $p < 0.001$. *Bold* = p < .05. *SII* = speech intelligibility index; *SE* = standard error.

Predictors	*Estimates*	*SE*	*p*
Intercept (Children, FC Off, Words)* **	75.7	19.9	<.001
Adults	-22.1	29.0	.447
FC On	-24.1	15.5	.122
Sentences	-12.3	15.5	.430
Aided SII* **	**-107.1**	**30.0**	**<.001**
Adults x FC On*	**45.0**	**22.6**	**.049**
Adults x Sentences	26.0	22.6	.253
FC on x Sentences	21.8	22.0	.323
Adults x Aided SII	41.7	44.0	.345
FC on x Aided SII	34.6	23.4	.142
Sentences x Aided SII	17.4	23.4	.460
Adults x FC On x Sentences*	**-71.2**	**32.0**	**.028**
Adults x FC On x Aided SII*	**-69.2**	**34.4**	**.046**
Adults x Sentences x Aided SII	-42.8	34.4	.216
FC on x Sentences x Aided SII	-32.8	33.1	.324
Adults x FC On x Sentences x Aided SII*	**112.7**	**48.6**	**.022**

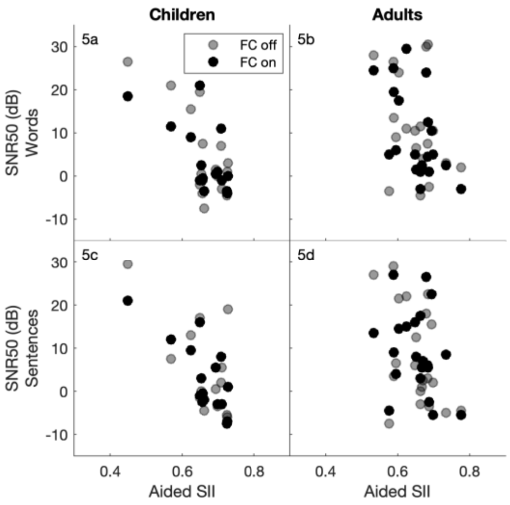
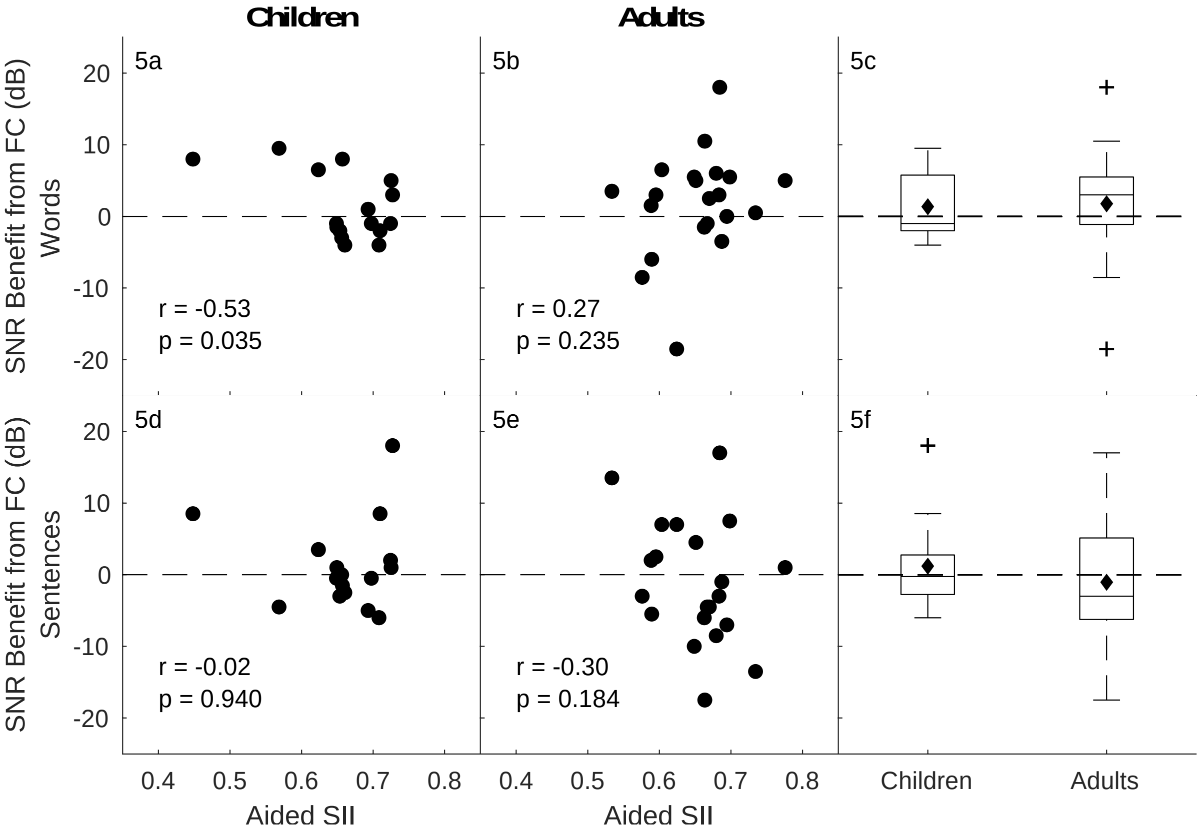


Figure 4. The SNR50 as a function of better-ear aided SII for each processing condition (FC on, FC off), by age group (children: Figures 5a and 5c; adults: Figures 5b and 5d) and stimulus type (words: Figures 5a and 5b; sentences: Figures 5c and 5d). *FC* = frequency composition; *SII* = speech intelligibility index; *SNR50* = signal-to-noise ratio at 50% correct.

There was potentially an influential case, a child participant with an aided SII of .45 (the lowest SII). While Cook's distance did not indicate a strong influence for the overall model, it did indicate a strong influence (>1) of this participant for WDRC with sentence. However, removal of this participant from the linear mixed model (Table 3) did not change the interpretation of the significant 4-way interaction and while the removal of this participant decreased the bivariate correlation of FC benefit for words to SII from -.53 to -.40 (*p*=.140), removal of other participants also changed the significance of the correlation, suggesting that the change in significance was due to a lack of power. The right column of Figure 5 depicts the benefit of FC as boxplots and both wide variance in FC benefit (range: -18.5 to 18 dB) and that the benefit of FC was evenly distributed above and below 0 dB.

Figure 5. Individual signal-to-noise ratio (SNR50) for frequency composition (FC) off minus SNR50 for FC on, by aided speech intelligibility index (SII), age group (children: Figures 5a and 5d; adults: Figures 5b and 5e), stimulus type (words: Figures 5a and 5b; sentences: Figures 5d and 5e). Solid lines depict model estimates for FC benefit. SNR50 values above the dashed lines show better performance with FC on and SNR50 values below the dashed lines show better performance with FC off. Text inserts provide the bivariate correlations for each condition. Figures 5c and 5f depict benefit of FC as boxplots.



DISCUSSION

This experiment was primarily designed to test the following research question: can the aided SII be used to predict individual benefit in speech recognition with FC? This question was answered by using recently developed stimuli (Spratford et al., 2017) to obtain word and sentence recognition thresholds in noise—with and without FC—using a hearing-aid simulator. It was observed that child participants who had a lower-aided SII showed a greater benefit from FC for their word recognition threshold (*r*=-.53), however, this finding only occurred for word recognition with FC in children but not for sentence recognition or for the adults participants. While these results provide some evidence for the efficacy of FC processing, further studies are needed to determine the generalizability of these results. Specifically, the strongest benefit of FC occurred for the children with an aided SII less than approximately .7 (see Figure 5), however, this finding did not generalize to most participants or to the sentence condition. For participants with a high aided SII without FC, the potential to improve audibility with FC—relative to individuals with a low-aided SII—is diminished. This limited potential to improve audibility, combined with the potential for increased masking, suggests that FC may not be clinically warranted, especially due to the potential for increased masking that could distort the original speech signal.

The relationship of audibility to benefit from frequency lowering is contentious. Data obtained using a different frequency-lowering algorithm where participants with higher PTA (Souza et al., 2013) or better-aided SII with than without NFC (McCreery et al., 2014) experienced better speech recognition with frequency lowering, however, one study documented greater benefit for those with less, not more, hearing loss (Brennan et al. 2017). Because the observed relationship of aided SII to FC benefit did not extend to the adult participants or—for the child participants—to the sentence stimuli, the results of this study do not lend strong support to the argument that benefit from frequency lowering is greater for those with less audibility or to the contention of Kirby et al. (2017) that FC benefit might be limited to those with more severe hearing loss (i.e. less audibility).

As documented in a meta-analysis by Simpson et al. (2018), larger benefits of frequency lowering have previously been observed for stimuli with less than more contextual information (i.e. consonants versus sentences). Thus, a larger benefit of FC was predicted for the word than sentence stimuli. While the low-context sentences did not contain as much context as regular sentences, the sentences contained syntax information; whereas the words did not. Due to children relying less on higher-order cognitive and linguistic skills to decode speech (McCreery et al. 2019), we also hypothesized that a larger benefit of FC would occur for the child than the adult participants. While FC benefit was greater for the child (1.3 dB) than adult participants (0.4 dB), this difference was not statistically or clinically significant. These results then, do not provide strong support for the argument that benefit from frequency lowering differs by the availability of contextual information or age.

The participants may not have been able to take advantage of the increased audibility provided by FC—possibly due to an insufficient acclimatization period or masking; however, acclimatization is an unlikely reason. Specifically, while it is possible that an extended wearing time with real hearing aids could have resulted in improvements in SNR50 with FC on relative to FC off, the current evidence provides limited support for this notion (Kirby et al., 2017; Salorio-Corbetto et al., 2017). Masking of the lowered sounds by the extant sounds (or vice versa) may have contributed to the lack of benefit from FC processing. Consistent with this notion, Miller et al. (2016) observed equivalent SNR50 performance for a frequency lowering algorithm that did not overlap energy from the source and destination regions (nonlinear frequency compression) and, in that same study, a detriment in SNR50 was observed with frequency transposition, a frequency-lowering algorithm that overlaps energy from the source region with that in the destination region.

There was one methodological variation between the two groups that future work should consider. For the same degree of hearing loss, the adult participants were prescribed less output using DSL adult than the child participants using DSL child. This difference does not appear to have contributed significantly, as there was not a significant difference in FC benefit for the adult relative to child participants. However, due to a lower sensation level with DSL adult than child, audibility of the lowered information with DSL adult might be insufficient to improve SNR50; i.e., it is conceivable that benefit from frequency lowering could differ by prescriptive procedure.

CONCLUSION

The primary aim of this study was to evaluate the impact of audibility on speech recognition in noise performance with FC for children and adults with hearing loss. For both groups, there was not a significant benefit of FC for both the word and sentence stimuli. Across participants, there was wide variance in FC benefit. FC benefit for the word, but not sentence condition, was tended to decrease with increased aided SII—i.e. child participants with less-aided SII were more likely to benefit from FC than those with greater-aided SII. Because this relationship was not observed for the sentence stimuli or for the adult participants, these data provide limited support for the notion that FC might be efficacious for patients who have a low-aided SII and future work is necessary to support or refute this observed relationship of aided SII to FC benefit.

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Declaration of Interest

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