2022

Effects of Hearing Aid Amplification on the Ability of Individuals With Hearing Loss to Perceive Spectral Information

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EFFECTS OF HEARING AID AMPLIFICATION ON THE ABILITY OF INDIVIDUALS WITH HEARING LOSS TO PERCEIVE SPECTRAL INFORMATION

An Undergraduate Honors Thesis
Submitted in Partial Fulfillment of
University Honors Program Requirements
University of Nebraska-Lincoln

by

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March 7, 2022

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Abstract

Individuals with sensorineural hearing loss often struggle to understand speech even with the use of hearing aids; simply making sounds louder is not enough. Listeners decode various speech sounds with the help of spectral information, but how hearing aid amplification affects individuals' ability to perceive those cues is not currently well understood. Altering the way hearing aids are programmed to provide amplification can potentially improve the ability of listeners with sensorineural hearing loss to access spectral information. The purpose of this study was to quantify the effects that hearing aid amplification has on the perception of spectral cues. Outcomes could help clinicians select hearing aid prescriptions that improve the adult listener's ability to perceive spectral cues in speech. Participants with sensorineural hearing loss (normal middle ear function) were tested in aided conditions including alteration of compression channels (4, 8, and 16). Psychophysical tuning curves were collected from each participant, with a target frequency of 2 kHz and a presentation level of 10 dB SL in reference to a threshold obtained in quiet conditions. Data were compared to psychophysical tuning curves collected from participants with normal hearing. We hypothesized that the 16-channel condition would produce psychophysical tuning curves that matched the normal hearing individuals' psychophysical tuning curves most accurately; an increased number of compression channels would provide better audibility across all frequencies, thereby improving access to spectral information. Indeed, as the number of compression channels was increased, the low-frequency side of the psychophysical tuning curves showed improvement.

Keywords: Amplification, Psychoacoustics, Psychophysical Tuning Curves, Sensorineural Hearing Loss

Appreciation

This project is a part of ongoing work in Dr. Brennan's laboratory. Dr. Brennan's work, within which this project is encompassed, has IRB approval (20181218892EP), is registered with clinicaltrials.gov (NCT03850678), and is funded by the National Institute on Deafness and Other Communication Disorders (R21 DC017588 03). Data collection for my portion of the project occurred over the Summer of 2021 as a part of the University of Nebraska – Lincoln's Undergraduate Creative Activities and Research Experience (UCARE) program. The authors would also like to thank Joshua Alexander for providing the hearing aid simulator code.

Effects of hearing aid amplification on the ability of individuals with hearing loss to perceive spectral information

I. INTRODUCTION

This study focuses on aspects of spectral resolution as they impact individuals with sensorineural hearing loss (SNHL). Spectral information refers to the relative level of frequencies and can change over time (Lutman et al., 1991; Moore, 1985a; Moore, 1996). Hearing aids are often thought of as helping those with hearing loss simply by increasing the volume of sounds in the listener's environment. However, it has been determined that even when sound is well above their threshold and the signal-to-noise ratio (SNR) is favorable, individuals with a hearing loss involving the cochlea still cannot hear very well (Bonding, 1979; Dreschler & Plomp, 1985). With this information, it is necessary to then look at how the programming of hearing aids impacts a listener's ability to pick up on the spectral information contained in the messages they are receiving from their environment.

The dynamic range of speech refers to the difference in level between the speech reception threshold in quiet and the highest comfortable level for speech (Moore et al., 1985b). Compression lets you amplify the soft sounds more than loud sounds, making a broader range of sounds accessible to hearing aid users. Studies discussed by Moore et al. (1985b) have found no considerable improvement of speech intelligibility in noise with the use of compression, and that speech intelligibility is often made worse by the use of compression compared to linear amplification. However, other studies show that the effects of reduced dynamic range in individuals with SNHL can be decreased with the help of hearing aids that use compression (Moore, 1996). Compression channels are set up in frequency bands; more channels mean fewer frequencies included within each channel. Because of this, there are a few factors discussed by Yund and Buckles (1995) that tend to vary with frequency—loudness discomfort levels, recruitment functions, and threshold elevations in particular—that can be amplified at different levels to account for differences, but only if those frequencies fall under different channels. Given the conflicting results on the relationship of compression to benefit, it is clear that a different approach to this problem is necessary.

Psychophysical tuning curves (PTCs) are used to “assess frequency selectivity of the auditory system and can detect and delimit ‘dead regions’ in the cochlea” (Sęk et al., 2005). PTCs are measured by presenting a signal at a fixed frequency and level and then introducing a masker whose level and center frequency are altered to find a threshold. Individuals with normal hearing (NH) produce PTC tips near the signal frequency with steeper slopes to the right of the tip (higher frequencies) and a shallower “tail” to the left of the tip (lower frequencies). Individuals with sensorineural hearing loss produce broader PTCs that will sometimes lack the sharp tip seen in the PTCs of listeners with normal hearing (Bonding, 1979; Carney & Nelson, 1983; Sęk et al., 2005). Studies have shown differences in PTCs between SNHL and NH listeners occurring when losses exceed 40 dB hearing level (HL) (Carney & Nelson, 1983). Something else to consider when comparing PTCs between SNHL and NH listeners is that differences could be due to off-frequency listening, not just frequency selectivity (Moore, 1985a).

Auditory filters can broaden with age, so the Moore (1985a) study noted difficulty determining if the broadening seen in their results was due to age or hearing loss in the group of older individuals with SNHL. The same study also found that the presentation level can affect the auditory filter; at higher levels, the filter can become significantly asymmetrical, with the low-frequency side getting shallower and the high-frequency side getting steeper. Nonetheless, it appears that individuals with hearing loss have more broadly tuned auditory filters than those with normal hearing (Dubno & Schaefer, 1992).

Numerous studies have discussed the benefit of the presence of compression or the speed of compression (Brennan et al., 2015; Kowalewski, 2020; Moore, 1985b, 1996) but few have looked at the benefit provided from specified numbers of compression channels (Alexander & Masterson, 2015; Bor et al., 2008; Yund & Buckles, 1995). The present study hopes to fill the gap in knowledge of how hearing-aid signal processing (essentially, hearing prescriptions) affects access to spectral information. The data collected here will provide critical information about ways to personalize the programming of compression channels within hearing aids for individual hearing aid users that can ultimately improve speech recognition for individuals with hearing loss.

We altered the number of compression channels (CC) between 4, 8, and 16 and expected that the 16-channel condition would produce the best sweeping psychophysical tuning curves (SW-PTCs) results. We attempted to find participants with qualifying sensorineural hearing loss who would be willing to return 2-3 times to complete all three of these tasks. We compared this data to a separate group of participants with normal hearing from which we gathered PTCs at .5 and 2 kHz (kilohertz) at three different intensity levels. We looked at which conditions produced the sharpest PTCs in SNHL participants since NH participants exhibited sharper tuning curves, as expected. We hypothesize that increasing the number of compression channels used to program hearing aids will optimize the dynamic range of hearing and provide better audibility across frequency, which would in turn improve access to the spectral information found in speech.

II. METHODS

a. Participants

Thirty-seven individuals with SNHL (age in years: mean = 69.9, standard deviation = 3.8) and eleven individuals with NH (age in years: mean = 65.6, standard deviation = 6.8) participated in this study. Inclusion criteria for the SNHL group included a pure tone average (PTA) of 1-, 2-, and 4-kHz between 35- and 65-dB HL, the threshold at 2 kHz $\geq$ 35 dB HL, no air-bone gap, and normal tympanometric results. Inclusion criteria for the NH group included thresholds $\leq$ 25 dB HL from .25-8 kHz. These criteria were applied to only the one ear that was tested. Before beginning the experiment, each participant underwent a series of tests including otoscopy, tympanometry, and audiometry.

All participant's air conduction thresholds (American National Standards Institute [ANSI], 2004) were obtained using pure tone audiometry (American Speech-Language-Hearing Association [ASHA], 2005) at octave frequencies from .25-8 kHz and the 6-kHz interoctave frequency with RadioEar DD450 headphones (Middlefart, Denmark). Other interoctave frequencies were also tested when the difference between air conduction thresholds at consecutive octave frequencies was greater than 20 dB. Bone conduction thresholds were obtained if the participant's threshold was above 25 dB HL at octave frequencies between .5 and 4 kHz. The average pure-tone air conduction thresholds are shown in Figure 1.

Participants were recruited from a list of previous participants in the Amplification and Perception Laboratory as well as the Barkley Memorial Center Speech-Language and Hearing Clinic and an email list distributed by the Osher Lifelong Learning Institute. Data were collected in the Amplification and Perception Laboratory at the University of Nebraska – Lincoln under approval from the Institutional Review Board (IRB). Participants consented to join the study and received a reimbursement of $15 per hour for their time.

b. Equipment

Digital stimuli were generated at a 22.05-kHz sampling rate via custom MATLAB (2018a) (MathWorks, Natick, Massachusetts) code on an iMac (Cupertino, California), routed through an RME Babyface soundcard (Haimhausen, Germany), and amplified by a HeadAmp 4 Pro headphone distribution amplifier (Baton Rouge, Louisiana). Stimuli were then presented to one randomly assigned ear via Sennheiser HD-25 headphones (Wedemark, Germany). Testing took place in a single-walled sound-attenuated room in the Amplification and Perception Laboratory. A touch screen monitor (Planar, PT2245PW, Beaverton, Oregon) was used for participants to select their responses.

c. Stimuli

Stimuli included a 2-kHz (500-ms duration) pure-tone target presented at 10 dB sensation level (SL) and a .32-kHz wide masker (700-ms duration) in which the center frequency varied from 1 to 3 kHz in 10-Hz steps. A 6-cc flat plate coupler and Larson Davis System 824 sound level meter (Depew, New York) were used for calibration. The 2-kHz target was chosen to test the frequency region that largely contributes to speech understanding (ANSI, 1997).

d. Amplification

Stimuli were amplified using the hearing aid simulator detailed in Brennan et al. (2015). The simulator utilized a filterbank, wide dynamic range compression, and output compression to produce hearing aid prescriptions in which the number of compression channels (4, 8, or 16) could be manipulated (Brennan et al., 2018). The SNHL group's hearing thresholds were entered into the hearing-aid simulator run through MATLAB (2018a). The hearing aid simulator was not used for the NH group, but they otherwise underwent the same procedures as the SNHL group.

e. Procedure

Participants were all given an explanation of the study and signed the appropriate IRB consent form. A questionnaire regarding hearing and education histories was filled out by the participant. All participants underwent otoscopy, tympanometry, and an audiogram to ensure normal middle ear function and qualification based on hearing loss. Participants in the SNHL group were tested at 2 kHz while participants in the NH group were tested at both .5- and 2-kHz (unaided). Participants with SNHL were tested with 4, 8, and 16 channels.

To find thresholds in quiet, the order of conditions was randomized, and the first condition was used for one practice run. A 3-interval alternative forced-choice pattern was used for obtaining the threshold. If more than six incorrect responses were observed at the maximum presentation level of 95 dB sound pressure level (dB SPL), the threshold was recorded as 98 dB SPL. If more than six correct responses were observed at the minimum presentation level of -15 dB SPL, the threshold was recorded as -18 dB SPL.

The threshold found in quiet was used to modify presentation levels of the target level used in the SW-PTCs tasks. The target level was set to 10 dB SL and the masker frequency and level was adaptively adjusted based on a single interval yes/no task (participants indicated that they either did or did not hear the pure-tone target). The level increased by 2 dB after one correct response and decreased by 2 dB after one incorrect response. Each run ended after completing a total of two-hundred trials ranging from 1- to 3-kHz in 10 Hz steps. The proportion of correct catch trials (in which no tone was presented, and the participant should indicate that they did not hear the tone) was recorded, and anything less than 80% resulted in reinstruction and an additional trial run.

f. Analysis

Data was collected from NH participants at .5 kHz and will be included in figures but not discussed in this paper. Conditions were averaged across three runs per participant, and Figures 2 and 3 plot the average for each condition across subjects. Psychophysical tuning curves were smoothed using a 10-point rolling average technique. Tuning curves were analyzed using a linear mixed-effects model (Table 1) to evaluate the effects of the number of compression channels on the low-frequency and high-frequency sides of the tuning curves.

III. RESULTS

a. Absolute threshold

Absolute threshold (threshold in quiet) for the 2-kHz target without the masker for all conditions is shown in Figure 2. There is no qualitative difference across conditions or between groups, presumably due to the use of the hearing aid simulator for the CC group. The absence of a difference between groups indicates that SNHL listeners were able to perform at levels comparable to NH listeners with the help of a hearing aid prescription.

b. Behavioral psychophysical tuning curves

The behavioral psychophysical tuning curves for both NH and CC (all channels) are depicted in Figure 3. The 16-channel PTC for CC appears closer to the shape of the NH PTC than the 4- and 8-channel PTCs do, indicating that the use of 16-channel in hearing aid programming is likely to restore more of the normal function than lower numbers of channels. As the number of compression channels for the CC group increased from 4 to 16, there was an improvement in the low-frequency side. Figure 4 shows the proportion of correct catch trials. For these presentations, no pure-tone target was presented, and participants should have indicated that they did not hear the tone. If a run resulted in a proportion correct of below 80%, the participant was reinstructed and completed an additional run.

The Q10 values for both NH and CC (all channels) are shown in Figure 5. Q10 quantifies the 10-dB down point relative to 2 kHz and is calculated as the frequency difference between the 10-dB down point divided by the tip frequency, which was 2 kHz in this study. A higher Q10 indicates that the tuning curve was sharper, which is what this study was looking for. The Q10 values of the SNHL group were not much different than those of the NH group, but there was an increase in Q10 (indicating a sharper tuning curve) among the SNHL group as the number of compression channels increased from 4 to 16. This can also be seen in Figure 3 where the 16-channel PTC has a significantly steeper slope on the high-frequency side than the 4- and 8-channel PTCs.

c. Linear mixed-effects model

The linear mixed-effects model in Table 1 compares the various conditions to a reference condition of 16 channels at 1 kHz. From this, it is evident that amplification improved the sharpness of tuning, with 16 channels of compression providing sharper tuning than 8- and 4-channels. The statistical model indicated that significantly greater masking occurred on the high- than the low-frequency side of the PTC. The 16-channel PTC was steeper on the low-frequency side than on the high-frequency side, again indicating that more masking occurred on the high-frequency side of the PTCs. The 4-channel PTCs were not as sharp as the 8-channel PTCs, which were also not as sharp as the 16-channel PTCs on the high-frequency side, showing that higher numbers of channels do in fact provide sharper tuning. The three-way interaction listed at the bottom of the table reveals that the relative sharpness of PTCs is different between channel conditions as well as between low and high frequencies.

IV. DISCUSSION

a. General discussion

The goal of the current study was to quantify the effects that hearing aid amplification, specifically the number of compression channels, has on the perception of spectral cues by individuals with SNHL. It was hypothesized that since increased numbers of compression channels provide better audibility across all frequencies (and therefore better access to spectral information) that the condition with 16 channels would produce SNHL PTCs that most closely match those gathered from NH individuals. To test this, we collected PTCs from individuals with SNHL and NH, altering the number of compression channels (4, 8, or 16) for the SNHL participants. Initial analysis involved looking for which condition(s) produced the sharpest SNHL PTCs since the NH PTCs are characterized by sharper tuning curves, as noted in previous studies of psychophysical tuning curves (Carney & Nelson, 1983; Strelcyk & Dau, 2009).

Other studies have evaluated the effects of the number of compression channels on speech recognition rather than psychophysical tuning curves. These will be discussed in-depth in the following section; however, it is worth mentioning that most of them found 8 channels to produce the best results in terms of participants' abilities to perceive the spectral information necessary for speech recognition (Alexander & Masterson, 2015; Bor et al, 2008; Yund & Buckles, 1994). While this contrasts the present study's results of 16 channels producing better results than 4- or 8-channels, it is important to remember that the PTCs were compared between NH and SNHL participants while speech recognition performance was compared between SNHL participants while both aided and unaided.

b. Speech recognition

This study only looked at PTCs, but other studies have investigated whether the number of channels affects speech recognition abilities. A study conducted by Bor et al. (2008) found that increasing the number of compression channels caused the spectral contrast of vowels to decrease, and that audibility did not have a significant effect on the identification of vowels. We cannot say whether our data aligns with this conclusion since this study did not measure vowel recognition. However, a prescriptive procedure was not used by Bor et al.; they excluded individually prescribed gain and instead controlled overall SPL levels. This procedure likely introduced greater distortion, and in turn, decreased benefits in audibility.

A study by Alexander & Masterson (2015) also looked at how the number of compression channels affects speech recognition but included another factor (release time) that was considered jointly to the number of compression channels. They found that across the speech recognition results were best when using 8 channels when used in combination with varying lengths of release time. The authors noted that there are multiple acoustic elements that likely contributed to why individuals produced varying results. Specifically, participants experienced tradeoffs with audibility and the acoustic elements that varied based on each of their individual hearing losses. Part of this may also have been due to the fact that participants only used the study settings during the data collection stage; they may have not been provided adequate time to adjust to the devices in their own lives.

The results found in the current study—that 16-channel compression produced statistically significant differences in SNHL PTCs—are similar to the findings of Yund and Buckles (1995), who state that participant speech recognition increased as channels increased from 4 to 8 and then did not change significantly between 8- and 16-channels. While Yund and

Buckles used speech sound stimuli rather than pure tone stimuli, the results of both their study and the current study support the claim that "more channels should provide a better fit to the hearing loss and also better operation in a larger variety of sound environments" (Yund & Buckles, 1995). Essentially, having more compression channels gives the clinician more flexibility when it comes to programming how the hearing aids process sounds across the range of frequencies. Consider a patient who has a severe hearing loss in the high frequencies but a moderate hearing loss in the low frequencies. Being able to add more gain to the specific high frequencies where it is needed and less gain to the low frequencies where it may not be needed at as high of an intensity could provide them with better access to spectral information than if a similar amount of gain was prescribed across all frequencies. This is much easier to achieve in the middle-range frequencies when the clinician can split them into smaller bands to provide more precise adjustments.

c. Implications

Outcomes could help clinicians select hearing aid prescriptions that increase the dynamic range and therefore improve the adult listener's ability to perceive spectral cues in speech. While 16-channel compression did not produce PTCs as sharp as those seen from NH listeners, there was still a significant change from the 4- and 8-channel conditions to the 16-channel condition. With the use of 16-channels in compression programming, clinicians can provide more personalized prescriptions that improve audibility for their patients across all frequencies. It is possible that other parameters, decision variables, or auditory processing could better explain the PTCs observed in this study. These would be worth looking into in future studies, as well as the inclusion of the middle-ear reflex, efferent pathways, or inhibition.

V. CONCLUSION

This study will hopefully help clinicians in selecting hearing aid prescriptions that improve the adult listener’s ability to perceive spectral cues present in speech signals. To determine the appropriate number of compression channels to use in prescriptions, this study altered the number of compression channels (4, 8, or 16) and collected PTCs from individuals with SNHL. The study found that the 16-channel condition produced the sharpest PTCs—that is, the 16-channel PTCs were the most similar to the PTCs gathered from NH individuals. This means that if clinicians utilize 16-channel compression functions in hearing aid programming, they are likely to restore more of their patients’ normal function than if they were to use a lower number of channels. In the future, it would be beneficial to use the information gathered here and use a speech signal rather than a pure-tone signal. These tests were performed in a sound-treated booth under ideal listening conditions; adding in factors such as room acoustics, multiple speakers, and even just speech rather than pure tones will make the tasks significantly harder (Helfer & Wilber, 1990).

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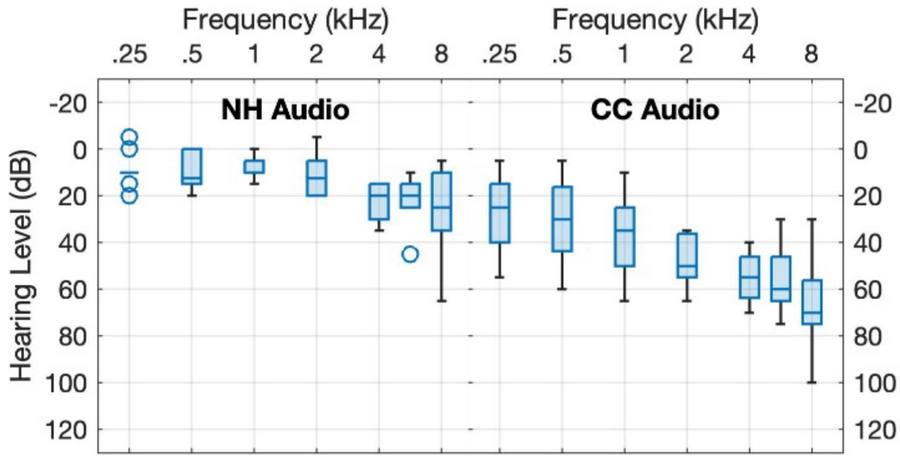

FIGURE 1. Audiometric thresholds of the participants, separated by normal hearing (left) and sensorineural hearing loss (right). The boxes depict the 25th through 75th percentiles, with the horizontal line representing the median. The error bars represent 2.7 standard deviations or the most extreme value that is not an outlier, whichever is lower. The circles represent outliers (data over 2.7 standard deviations).

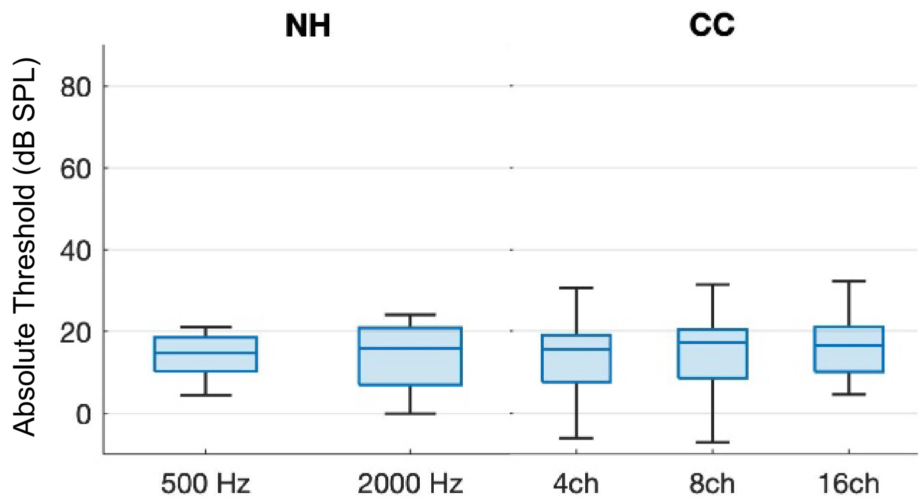

FIGURE 2. Absolute threshold values in dB SPL, separated by normal hearing (left) and compression channels (right) conditions. Qualitatively, the threshold did not differ across conditions or between groups. The boxes depict the 25th through 75th percentiles, with the horizontal line representing the median. The error bars represent 2.7 standard deviations or the most extreme value that is not an outlier, whichever is lower.

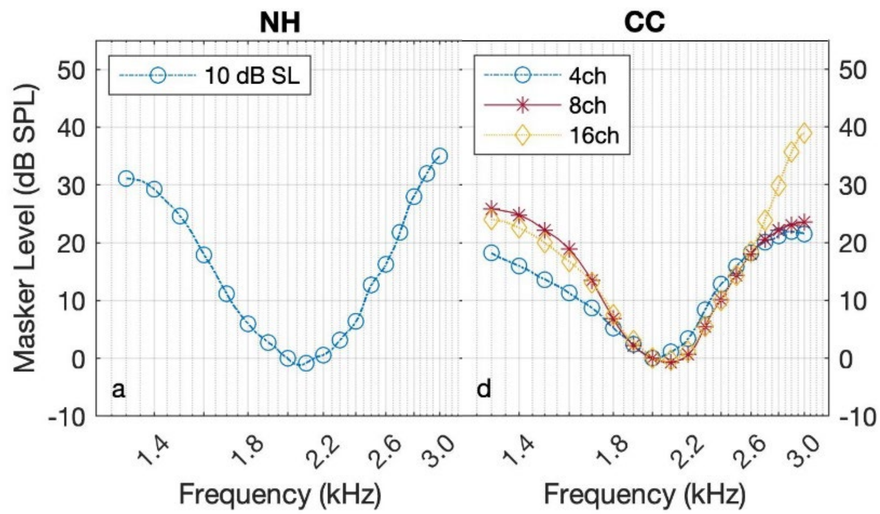

FIGURE 3. PTC curves for each condition, separated by normal hearing (left) and compression channels (right) conditions. The number of channels for CC conditions is indicated by the figure legend. NH participants were tested unaided at three sensation levels, but only 10 dB SL is presented here. PTCs were significantly sharper for 16-channels than 8-channels on the high-frequency side and 4-channels on both the low and high-frequency sides.

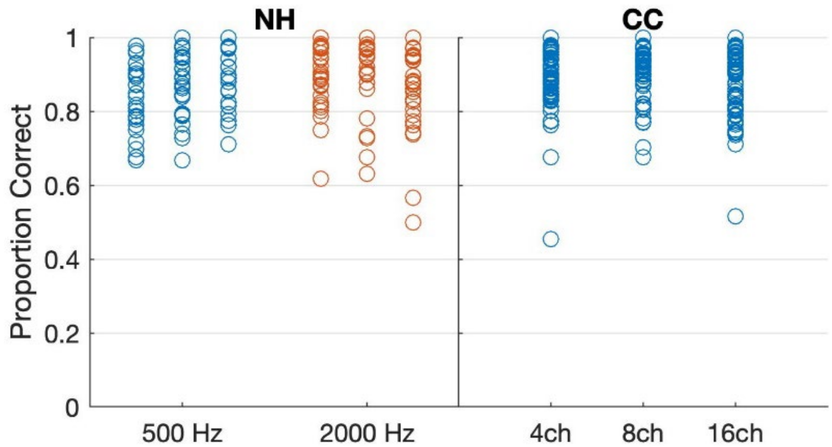

FIGURE 4. The proportion of catch trials each participant got correct, separated by normal hearing (left) and compression channels (right) conditions. Each circle in the figure represents a single run by each participant. Data were collected at .5 kHz (left side red) for NH in addition to the 2 kHz (left side blue) reported.

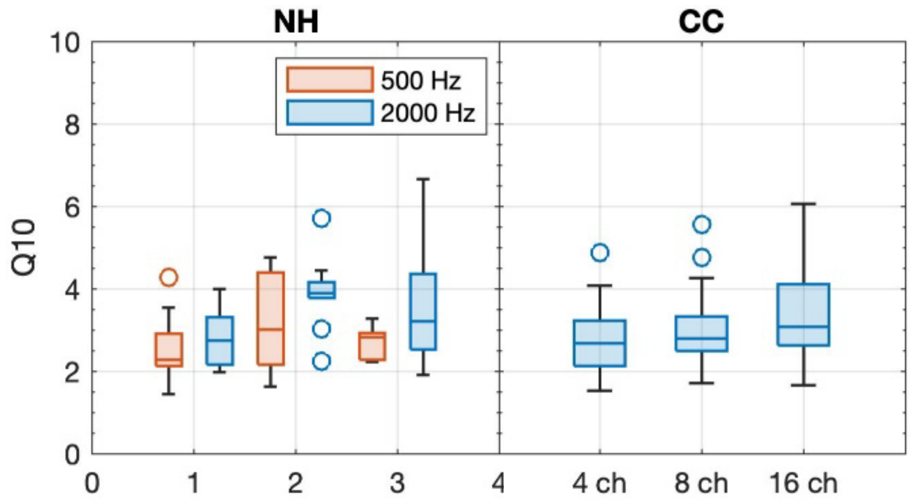

FIGURE 5. Q10 values, separated by normal hearing (left) and compression channels (right) conditions. 1, 2, and 3 correspond to 10-, 35-, and 55-dB SL, respectively. The boxes depict the 25^{th} through 75^{th} percentiles, with the horizontal line representing the median. The error bars represent 2.7 standard deviations or the most extreme value that is not an outlier, whichever is lower. Data were collected at .5 kHz (left side red) for NH in addition to the 2 kHz (left side blue) reported.

TABLE 1. Linear mixed-effects model evaluating the various conditions used in this study and their interactions. The reference conditions were 16 channels at 1 kHz and the low-frequency side of the PTC. Significant p-values have been bolded. The estimate is the predicted amount of masking by the reference condition at the intercept. The rows labeled 4 Channels and 8 Channels depict that much less (if estimate is negative) or more (if estimate is positive) masking than the reference condition.

	Estimate	**Standard Error**	**t-value**	**p-value**
Intercept	36.224	1.010	35.857	**<.001**
4 Channels (Ch)	-6.821	0.595	-11.464	**<.001**
8 Channels (Ch)	4.520	0.590	7.660	**<.001**
High Frequency (HF) Side	4.737	0.494	9.582	**<.001**
Frequency ($\log_{10}$)	-109.290	2.013	-54.300	**<.001**
4 Ch x HF Side	-6.343	0.705	-9.001	**<.001**
8 Ch x HF Side	-16.110	0.699	-23.044	**<.001**
4 Ch x Frequency ($\log_{10}$)	16.856	2.869	5.875	**<.001**
8 Ch x Frequency ($\log_{10}$)	-17.354	2.846	-6.097	**<.001**
HF Side x Frequency ($\log_{10}$)	-40.931	2.461	-16.635	**<.001**
4 Ch x HF Side x Frequency ($\log_{10}$)	48.137	3.508	13.723	**<.001**
8 Ch x HF Side x Frequency ($\log_{10}$)	66.885	3.480	19.221	**<.001**