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### Authors

Gilbert, Melanie L  
Deroche, Mickael LD  
Jiradejvong, Patpong  
et al.

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# Cochlear Implant Compression Optimization for Musical Sound Quality in MED-EL Users

Melanie L. Gilbert,<sup>1</sup> Mickael L. D. Deroche,<sup>2</sup> Patpong Jiradejvong,<sup>1</sup>  
Karen Chan Barrett,<sup>1</sup> and Charles J. Limb<sup>1</sup>

**Objectives:** Variations in loudness are a fundamental component of the music listening experience. Cochlear implant (CI) processing, including amplitude compression, and a degraded auditory system may further degrade these loudness cues and decrease the enjoyment of music listening. This study aimed to identify optimal CI sound processor compression settings to improve music sound quality for CI users.

**Design:** Fourteen adult MED-EL CI recipients participated (Experiment No. 1:  $n = 17$  ears; Experiment No. 2:  $n = 11$  ears) in the study. A software application using a modified comparison category rating (CCR) test method allowed participants to compare and rate the sound quality of various CI compression settings while listening to 25 real-world music clips. The two compression settings studied were (1) Maplaw, which informs audibility and compression of soft level sounds, and (2) automatic gain control (AGC), which applies compression to loud sounds. For each experiment, one compression setting (Maplaw or AGC) was held at the default, while the other was varied according to the values available in the clinical CI programming software. Experiment No. 1 compared Maplaw settings of 500, 1000 (default), and 2000. Experiment No. 2 compared AGC settings of 2.5:1, 3:1 (default), and 3.5:1.

**Results:** In Experiment No. 1, the group preferred a higher Maplaw setting of 2000 over the default Maplaw setting of 1000 ( $p = 0.003$ ) for music listening. There was no significant difference in music sound quality between the Maplaw setting of 500 and the default setting ( $p = 0.278$ ). In Experiment No. 2, a main effect of AGC setting was found; however, no significant difference in sound quality ratings for pairwise comparisons were found between the experimental settings and the default setting (2.5:1 versus 3:1 at  $p = 0.546$ ; 3.5:1 versus 3:1 at  $p = 0.059$ ).

**Conclusions:** CI users reported improvements in music sound quality with higher than default Maplaw or AGC settings. Thus, participants preferred slightly higher compression for music listening, with results having clinical implications for improving music perception in CI users.

**Key words:** Automatic gain control, Cochlear implants, Compression, Maplaw, Music perception.



This article has received OSF badges for Open Data and Open Material.

(Ear & Hearing XXX;XX;00–00)

## INTRODUCTION

Cochlear implants (CIs) are surgically implanted devices, which partially restore hearing to individuals with moderate to profound sensorineural hearing loss and poor speech recognition scores. As

CIs have become the standard of care over recent years, CI signal processing has greatly improved and is now able to provide users with very good speech recognition in quiet (Holden et al. 2013). Nevertheless, more complex auditory stimuli such as speech recognition in noise continues to be an area of significant difficulty for CI recipients (Wilson & Dorman 2018), and, along these lines, significant variability exists among CI users in terms of both appreciation of music and accuracy of music appraisal, with few reliable predictors of such abilities (Gfeller et al. 2008; Philips et al. 2012; Moran et al. 2016). Music is a complex signal, much more so than speech, and there is significant room for improvement for CI users in the many aspects of music listening, such as pitch discrimination, timbre perception, melody recognition, and dynamic range (DR) perception (Roy et al. 2012a,b; Limb & Roy 2014; Roy et al. 2015a,b; Caldwell et al. 2017; Jiam et al. 2019). Since CI users often report music stimuli as unenjoyable to listen to, studies that better elucidate the elaborate structure of music and their processing in CIs offer unique insight and creative solutions to this issue.

A broad range of efforts have already been made to improve music appreciation in CI users, including music preprocessing methods, sound coding strategies, and improved stimulation modes (Nogueira et al. 2019). Algorithms that assess the degree of musical stimuli complexity (Buyens et al. 2017; Nagathil et al. 2018), and others which reduce this complexity directly (e.g., through harmony attenuation) have been created (Nagathil et al. 2017). CI users have been shown to prefer solo instrumentation and predictably structured music over multi-instrumentation and unpredictable structures (Limb & Roy 2014). Additionally, music preprocessing strategies, which alter the music directly, have pointed to CI listener preferences for vocal amplification, accentuation of bass lines and drums, and stereo separation of accompanying instruments (Buyens et al. 2014; Buyens et al. 2015; Gajęcki & Nogueira 2018; Tahmasebi et al. 2020).

While these strategies are a critical means to achieving better music enjoyment in CI users, many studies have alternatively tuned and altered built-in parameters of CI devices for this same goal. Several of these have looked at modifying sound coding strategies with respect to spectral resolution and frequency distribution, which have reportedly led to improvements in melody and timbre recognition (Li et al. 2013; Wouters et al. 2015; Nogueira et al. 2019). It should be noted that each CI manufacturer utilizes a continuous interleaved sampling (CIS)-based coding strategy, but that each implementation is unique; strategies that work for a certain set of devices are not necessarily generalizable to others. More recently, current steering and novel stimulation modes have emerged as another technique to improve both speech and music perception. With the aim of reducing broad current spread, current steering techniques (e.g., phantom electrode stimulation), have shown clinical relevance in improving low high-frequency balance and general music perception in CI users (Nogueira et al. 2009, 2015).

<sup>1</sup>Department of Otolaryngology-Head and Neck Surgery, University of California, San Francisco, California, USA; and <sup>2</sup>Department of Psychology, Concordia University, Montreal, QC, Canada.

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Significant strides have been made across this field, as described in the studies above. However, there is a dearth of studies specifically examining the role of DR compression on music enjoyment in CI users. A specific area of sound perception that can be difficult to encode for a CI listener is the DR of sound intensity, ranging from very soft to very loud. According to Zeng (2004), the normal hearing (NH) human ear can comfortably perceive a span of about 100 dB, with 60 to 100 discriminable steps delineating the incremental range from the softest sound heard to the loudest sound tolerable. An ear with a CI, however, has a DR of only 6 to 20 dB, with around 20 discriminable steps (Zeng 2004). This limited DR of the implanted ear requires that the input signal be heavily compressed to present the listener with an adequate representation of speech and environmental sounds. However, it is worth noting that increasing compression ratios (e.g., from 1:2 to 1:3) reduces modulation depth of the audio signal to CI devices, which thereby reduces loudness peaks that may help a CI user distinguish between speech and background noise. A limited DR is problematic for music perception because music typically has a wide DR, with the Classical genre having the largest (Kirchberger & Russo 2016). In music, variations in loudness are a fundamental component of the listening experience and provide important cues (e.g., emotional content) to the listener. The variation in DR can occur over just 1–2 seconds, or also over the course of several minutes, and the fluctuations may provide the listener with feelings of excitement or suspense (e.g., the theme from the movie *Jaws*).

Two studies altered the compression of music directly, before CI processing. The first was a study by Halliwell et al. (2015) which found that CI listeners did not prefer music that had an input compression of 1.5:1 applied to the music before the experiment as compared to original unaltered music samples. The second was previous work from our laboratory, in which we assessed the effect of compression on music for both NH and CI subjects (Gilbert et al. 2019). The study used the Multiple Stimulus with Hidden Reference and Anchor (MUSHRA) test paradigm to compare NH listeners and CI users' abilities to detect and rate the sound quality of commercial music with additional compression applied directly to the audio clips via Adobe Audition software (San Jose, CA). The MUSHRA test is a tool used to assess relative changes in the perceived sound quality of music across increasingly degraded listening conditions. In the 2019 study, multiple iterations of a compression algorithm were applied to music clips across various musical genres. Subjects were also presented with a Reference excerpt, which was the original music clip without any additional compression applied, and were asked to rate the sound quality of the compressed clips compared to the Reference. It was found that both the NH and CI groups could discriminate between the original and the compressed music clips, although the CI group was less sensitive to the effects of the compression than the NH group. In other words, both NH and CI groups could detect sound quality differences as a function of compression level, but the discriminatory ability of the CI group was blunted compared to the NH group.

No studies were found; however, that specifically address optimal amplitude mapping functions of CIs for music appreciation. In the present study, we independently manipulated two parameters that control DR compression in MED-EL CIs to evaluate their impact on CI recipients' appreciation of music quality. In the MED-EL CI system, DR compression is implemented via the Maplaw and automatic gain control (AGC) parameters (Stöbich et al. 1999; Vaerenberg et al. 2014). The

electrical (output) DR is defined on a per-channel basis as the difference in charge levels between the maximum comfort level (MCL) and threshold of audibility (THR).

The Maplaw determines the steepness of the curve of loudness growth within the electrical DR of the channels (Vaerenberg et al. 2014), as illustrated in Figure 1. Changing the Maplaw setting primarily affects the loudness perception of sounds ranging from the soft to mid level. The default Maplaw setting in the programming software is 500, and the available range is 0 to 8000. A higher Maplaw makes soft sounds more audible by applying greater levels of compression to the sounds below the knee point, whereas a lower Maplaw reduces the prominence of soft- to mid-level sounds and allows for greater modulation depth. The Maplaw setting can affect speech recognition, and the literature suggests that a Maplaw in the range of 500 to 1000 is ideal for soft speech in quiet, and average-level speech in both quiet and in noise (Spahr & Dorman 2005).

AGC of the MED-EL system is a front-end feature that applies compression to average and loud sounds and is designed to maximize speech recognition while preserving comfort for transient and very loud sounds (Loizou 1999). The MED-EL system utilizes a dual-loop AGC with slow and fast detectors. The slow detector monitors the acoustic environment and compensates for variations in the overall level of sound, whereas the fast detector identifies and quickly reduces gain for loud transient sounds (Stöbich et al. 1999; Hochmair et al. 2006). The knee point of the AGC can be manipulated within the MED-EL system by changing the sensitivity of the microphone(s), with the lowest sensitivity setting corresponding to the highest knee point and the highest sensitivity setting corresponding to the

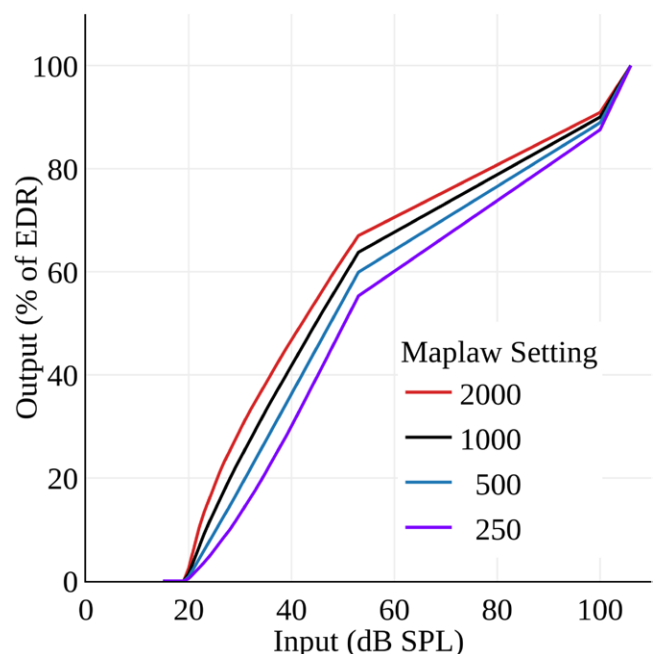


Fig. 1. Input-output functions for Maplaw settings. Maplaw primarily affects the perceived loudness of soft mid-level sounds. The x axis represents the level of the incoming sound in sound pressure level (SPL) in decibels (dB). The y axis represents the corresponding charge level delivered to the cochlear implant (CI), displayed as a percentage of electric dynamic range (EDR). Each line on the graph represents the input-output function corresponding to a particular Maplaw, ranging from highly compressed (2000) to less compressed (250).

lowest knee point. The AGC settings available in the programming software are: off, 2:1, 2.5:1, 3:1 (default), and 3.5:1. As illustrated in Figure 2, a higher AGC compression ratio (e.g., 3.5:1) means more compression is applied to sounds above the knee point, and thus more overall gain is applied throughout the input DR. Lowering the AGC (e.g., 2:1) necessitates raising the MCLs to ensure that the whole setting is not too soft, which means very loud sounds (e.g., door slam), consequently can be uncomfortably loud in some cases. For music perception, however, some people may prefer less compression so they can better appreciate a fuller DR of the music. Within the MED-EL system, any sound at or above 106 dB SPL is stimulated at MCL; the upper limit for signal level is 100 dB SPL with 6 dB headroom available to allow for rapid fluctuations and transient sounds (Katelyn Glassman & Josh Stohl, Reference Note 1).

A critically important unanswered question in the literature pertains to what the specific impact of different CI loudness-processing algorithms is on appreciation of music. The purpose of this study was to identify Maplaw and AGC sound processing settings that will optimize the CI handling of compression with regards to music sound quality for MED-EL CI users. We hypothesized that changing the compression ratios would have a significant impact on musical sound quality for CI users. More specifically, we anticipated that CI users might prefer less DR compression, as it would provide greater amplitude modulation depth of the auditory signal. To better understand our study results, we also wanted to examine whether the following demographic and CI factors impacted subjects' ratings of sound quality as a function of compression ratios: musical genre, CI

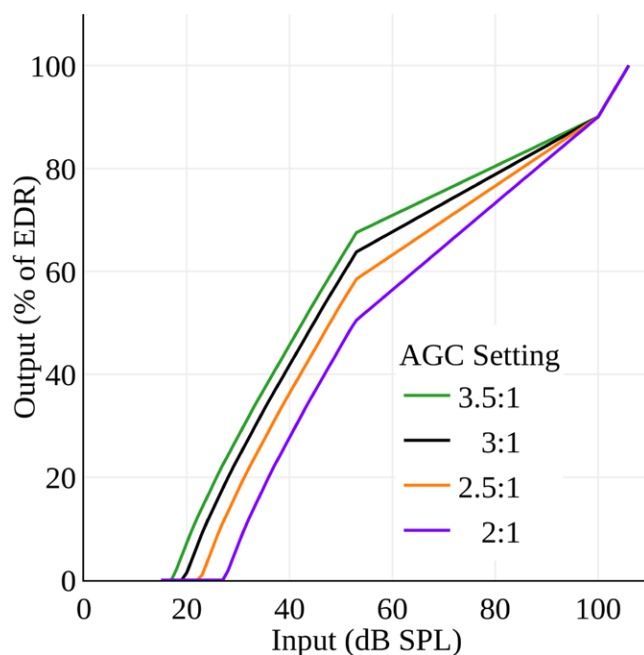


Fig. 2. Input–output functions for automatic gain control (AGC) settings. The AGC primarily affects the perceived loudness of loud sounds. The x axis represents the level of the incoming sound in sound pressure level (SPL) in decibels (dB). The y axis represents the corresponding charge level delivered to the cochlear implant (CI), displayed as a percentage of electric dynamic range (EDR). Each line on the graph represents the input–output function corresponding to a particular AGC, ranging from the most compressed (3.5:1) to least compressed (2:1) settings available in the CI programming software.

laterality, gender, threshold-level setting, electrode array length, processing strategy, number of active electrodes, number of fine structure channels, and musical training; these additional analyses may be found in the Figures 1–8 in Supplemental Digital Content 1–8, <http://links.lww.com/EANDH/A925>; <http://links.lww.com/EANDH/A926>; <http://links.lww.com/EANDH/A927>; <http://links.lww.com/EANDH/A928>; <http://links.lww.com/EANDH/A929>; <http://links.lww.com/EANDH/A930>; <http://links.lww.com/EANDH/A931>; <http://links.lww.com/EANDH/A932>; and Supplementary Data Analysis in Supplemental Digital Content 9, <http://links.lww.com/EANDH/A924>.

## MATERIALS AND METHODS

### Subjects

Fourteen MED-EL CI recipients (7 men and 7 women, average age 60.3 years  $\pm$  one standard deviation of 13.5 years) participated in the study. Four subjects were bilaterally implanted and 10 unilaterally implanted, yielding 18 CI ears tested. In Experiment No. 1, Maplaw manipulations were studied in 17 CI ears and in Experiment No. 2, AGC manipulations were studied in 11 CI ears.

Thirteen CI recipients were postlingually deafened and 1 was prelingually deafened; all used oral/aural communication as their primary method of communication. The mean length of implant use was  $3.4 \pm 2.3$  years and the mean duration of severe to profound hearing loss before implantation was  $8.4 \pm 12.9$  years (range: <0.1 to 47.2 years). The CI users utilized a variety of devices and processing strategies (Table 1). Some of the subjects used a different sound processor model in day-to-day listening than the model used for this research experiment (i.e., a Sonnet), which may have affected results. The Institutional Review Board at the University of California, San Francisco (UCSF) approved this study, and informed consent was obtained from all participants.

Nine subjects reported formal music training, beginning at age  $8.4 \pm 5.4$  years and lasting  $9.0 \pm 7.3$  years. Of those nine subjects, three reported being self-taught musicians as did one additional subject who had no formal music training, with training beginning at age  $32.0 \pm 19.2$  years and lasting for  $3.9 \pm 2.2$  years. Six of the CI subjects reported that they do not listen to music in their day-to-day life, while the other eight subjects listen to music an average of  $6.7 \pm 4.3$  hours/week (range: 2 to 15 hours/week).

Most study subjects were using clinical default settings for Maplaw (500, 1000) and AGC (3:1). For the CI ears that were included in Experiment No. 1, three used Maplaw of 500, 12 used Maplaw of 1000–1024, and two used Maplaw of 1500. Of the CI ears included in Experiment No. 2, only one was using an AGC setting (3.5:1) in their clinical program different than the default setting (3:1).

### Musical Stimuli

A corpus of 25 real-world music clips assembled during earlier studies was used (Roy et al. 2012a,b). Each clip is 5 seconds long; there are five clips from each of five common musical genres (Classical, Jazz, Country, Rock, and Hip-Hop), and 60% of clips are commonly known while the other 40% are considered obscure. See Roy et al. (2012a) for additional details regarding the selection of musical clips. Music clips were each normalized to 65 dBA. The average acoustic DR for the stimuli

TABLE 1. Subject demographics

| ID No. | Ear | Age (yrs) | DOD (yrs) | Length CI Use (yrs) | Length Musical Training (yrs) | Etiology        | Sound Processor Model | Implant Model  | Electrode Array | Processing Strategy | Maplaw Experiment Participant | AGC Experiment Participant | Incoming THR Setting | THR Used for Testing | Incoming Maplaw Setting | Incoming AGC Setting |
|--------|-----|-----------|-----------|---------------------|-------------------------------|-----------------|-----------------------|----------------|-----------------|---------------------|-------------------------------|----------------------------|----------------------|----------------------|-------------------------|----------------------|
| 1      | R   | 53.8      | 0.5       | 7.2                 | 0                             | Sudden SNHL     | Rondo                 | Sonata Concert | Standard        | FS4-p               | x                             |                            | Meas                 | Meas                 | 1000                    | 3:1                  |
| 1      | L   | 53.8      | 3.6       | 4.0                 | 0                             | Sudden SNHL     | Rondo                 | Concert        | Flex28          | FS4-p               |                               | x                          | Meas                 | Meas                 | 1000                    | 3:1                  |
| 2      | L   | 48.9      | 47.2      | 1.6                 | 10.5                          | Unknown         | Sonnet                | Synchrony      | Flex28          | FS4                 | x                             |                            | 0%                   | 0%                   | 1000                    | 3:1                  |
| 3      | L   | 53.8      | 0.2       | 4.3                 | 12                            | Unknown         | Opus 2                | Concert        | Flex28          | FS4-p               | x                             |                            | 0%                   | 0%                   | 1024                    | 3.5:1                |
| 4      | R   | 71.4      | 0.4       | 2.9                 | 12                            | Genetic         | Sonnet                | Concert        | Flex24          | HDCIS               | x                             |                            | Meas                 | Meas                 | 500                     | 3:1                  |
| 4      | L   | 71.4      | 14.1      | 6.2                 | 12                            | Genetic         | Opus 2                | Sonata Concert | Medium          | FS4-p               | x                             |                            | 10%                  | 10%                  | 1000                    | 3:1                  |
| 5      | R   | 66.8      | 2.7       | 2.1                 | 0                             | Unknown         | Rondo                 | Concert        | Flex28          | FS4-p               | x                             | x                          | Meas                 | Meas                 | 1000                    | 3:1                  |
| 6      | R   | 35.8      | 15.1      | 0.7                 | 2                             | Genetic         | Sonnet                | Synchrony      | Flex28          | FS4                 | x                             |                            | 10%                  | 10%                  | 1000                    | 3.5:1                |
| 7      | R   | 59.3      | 0         | 2.2                 | 4                             | Genetic         | Sonnet                | Concert        | Flex28          | FS4-p               | x                             | x                          | Meas                 | Meas                 | 1000                    | 3:1                  |
| 7      | L   | 59.3      | 0         | 5.3                 | 4                             | Genetic         | Sonnet                | Concert        | Standard        | FS4                 | x                             | x                          | Meas                 | Meas                 | 1000                    | 3:1                  |
| 8      | R   | 75.8      | 0.5       | 3.3                 | 10                            | Unknown         | Rondo                 | Concert        | Flex24          | FSP                 | x                             |                            | 0%                   | 0%                   | 500                     | 3:1                  |
| 9      | R   | 56.4      | 4.5       | 1.9                 | 12                            | Meniere disease | Sonnet                | Synchrony      | Flex24          | FS4-p               | x                             | x                          | 10%                  | 10%                  | 1000                    | 3:1                  |
| 10     | L   | 87.6      | 0.3       | 1.8                 | 0                             | Unknown         | Sonnet                | Synchrony      | Flex24          | FS4                 | x                             | x                          | 10%                  | 10%                  | 1000                    | 3:1                  |
| 11     | R   | 55.8      | 1.9       | 6.9                 | 0                             | Unknown         | Sonnet                | Sonata         | Standard        | FSP                 | x                             |                            | 0%                   | 0%                   | 1500                    | 3:1                  |
| 11     | L   | 55.8      | 8.4       | 7.4                 | 0                             | Unknown         | Sonnet                | Sonata         | Standard        | FSP                 | x                             | x                          | 0%                   | 0%                   | 1500                    | 3.5:1                |
| 12     | R   | 72.7      | 10.3      | 0.4                 | 25                            | Unknown         | Sonnet EAS            | Synchrony      | Flex28          | FS4-p               | x                             | x                          | 10%                  | 10%                  | 1000                    | 3:1                  |
| 13     | R   | 60.5      | 7.4       | 3.2                 | 11                            | Unknown         | Rondo                 | Concert        | Flex24          | FS4                 | x                             | x                          | 0%                   | 0%                   | 1000                    | 3:1                  |
| 14     | R   | 45.5      | 34.5      | 0.6                 | 0                             | Sudden SNHL     | Sonnet                | Synchrony      | Standard        | FS4-p               | x                             | x                          | 5%                   | 5%                   | 500                     | 3:1                  |

AGC, automatic gain control; CI, cochlear implant; DOD, duration of deafness; EAS, electric acoustic stimulation; ID, identification; L, left; Meas, measured; R, right; SNHL, sensorineural hearing loss; THR, threshold.

was 32.7 dB; by genre, Hip-Hop: 39.9 dB, Jazz: 34.9 dB, Rock: 27.1 dB, Country: 29.0 dB, and Classical: 32.4 dB. For greater detail on the intensity-level distribution functions of the music clips, broken down to 1/3 octave bands and grouped by genre, see Figure 1 from Gilbert et al. (2019).

Testing took place in a calibrated sound booth. The stimuli were presented from a speaker located at 0 degrees azimuth with the listener seated 1 m from the speaker at an average RMS level of 65 dBA.

### Test Conditions

All CI recipients used a Sonnet sound processor designated for research use only. To increase consistency of audibility of musical clips across test subjects, their preferred everyday fittings were modified as follows: upper stimulation levels (MCLs) were loudness-balanced at 80% of incoming MCLs, and then the new MCLs were swept at 100% to ensure comfort. There were no predetermined restrictions imposed upon the patients' electrical DR (the difference between MCL and THR). Volume control was fixed at 100%. Microphone directionality and wind noise reduction features were disabled. Other parameters (except Maplaw, AGC, MCLs, and THRs) were not altered for either experiment, in order to minimize acclimatization effects to the new programs. For the first seven subjects, the subjects' threshold levels (THRs) were measured on each electrode and set at the highest inaudible level. For the remaining eight subjects, the THRs were set to either 0% or 10% of MCLs. Any changes to THRs were made before making other experimental changes.

We then created multiple new programs for the CI user with the Maestro software. For Experiment No. 1, Maplaw was varied (i.e., 500, 1000, and 2000), while AGC was fixed at the default (compression ratio 3:1 and sensitivity 75%). For Experiment No. 2, AGC compression ratio was varied (i.e., 2.5:1, 3:1, and 3.5:1), sensitivity was fixed at 100%, and Maplaw was fixed at the default (1000). In the MED-EL signal processing strategies, the sensitivity sets the knee point above which the AGC will become active. At the default sensitivity setting of 75%, the knee point is at 52.7 dB SPL. By changing the sensitivity to 100%, the AGC knee point is changed to 48 dB SPL and so more of the musical stimuli (delivered at 65 dBA) is presented in the DR where the AGC is active.

After the new programs were created, the MCLs were adjusted up or down globally in small (1%) increments in order to obtain equivalent loudness in all programs. This loudness-matching process involved presenting a pink noise at 65 dBA and switching back and forth between the default Maplaw program (program 1) and each of the other two experimental Maplaw programs in turn to ensure that programs 2 and 3 were loudness-matched to program 1. Once both programs 2 and 3 had been individually adjusted to match program 1, all three programs were cycled through a final time to confirm the pink noise was the same loudness level to the listener in each program. This process was then repeated with the three AGC programs.

Program 1 was always the program with both Maplaw and AGC set to defaults (Maplaw = 1000, AGC = 3:1), while programs 2 and 3 were experimental programs and the program order was not randomized. For Experiment No. 1, program 2 used Maplaw of 2000, and program 3 used Maplaw of 500. For Experiment No. 2, program 2 used AGC of 3.5:1 and program 3 used AGC of 2.5:1. It was important to rebalance the

loudness within these programs because, without doing so, programs with a higher Maplaw or AGC would seem louder to the CI user, and it is known from previous research that the loudness of music may significantly influence the sound quality perception (Vickers 2011). For the 10 subjects who completed both Experiments No. 1 and No. 2, eight subjects began with Experiment No. 1 and 2 subjects began with Experiment No. 2.

We began the experiments with the intention of including even lower (i.e., more linear) compression settings under the test conditions, but the first few subjects tested with these settings were unable to tolerate these programs. More specifically, when the Maplaw was decreased to 250 or the AGC was decreased to 2:1, the music clips became too soft overall to be evaluated fairly. We attempted to correct for this by increasing the MCLs globally to make the music clips equally loud under all of the conditions. Unfortunately, this resulted in the intensity peaks in the music clips becoming uncomfortably loud in the programs with the lowest compression settings, and therefore, those test conditions (i.e., Maplaw of 250 and AGC of 2:1) were discontinued.

CI users listened with the test ear only. If the nontest ear had any residual hearing, a foam earplug was used. In one case, a CI recipient had a Lyric hearing aid in the nontest ear that was situated deep in the ear canal and could not be removed for testing. The Lyric was therefore turned off and functioned as an earplug. All CI users were asked if they could hear the test stimuli with the nontest ear, while the earplug was in place and the CI on their test ear was turned off; all indicated they were not able to hear the stimuli with the nontest ear.

Participants completed the experiment using a Dell Latitude E7470. Subjects were given the option of using a touchscreen, mouse, or touchpad. The computer ran the program with MATLAB software version R2012b (Mathworks, Natick, MA).

## Test Paradigm

The method used for testing closely resembles a comparison category rating (CCR) approach, which allows for assessment of relative changes in the perceived sound quality of music across various listening conditions (ITU 1996). The present study utilized a user-controlled CCR method, which is different from the standard CCR in that the presentation order is not predetermined or randomized; the users may play the sound samples in any order and with the possibility of unlimited repetitions. Participants were asked to rate the relative sound quality of a particular music clip while using three different programs on their CI (“Prog 1,” “Prog 2,” and “Prog 3”).

The ratings were on a sliding scale with the following categorical labels: “Much better,” “Slightly better,” “Same as Prog 1,” “Slightly worse,” and “Much worse” (see Figure 3). The sliding scale corresponded to numbers from 0 to 200; scores from 0 to 99 represented sound quality worse than program 1, a score of 100 represented sound quality equal to program 1, and scores from 101 to 200 represented sound quality better than program 1. Program 1 was always set to 100, the midpoint (“Same as Prog 1”). The subjects were not explicitly required to use the whole range of the sliding scale. Although the term typically used to describe the results of a CCR-style test is the comparison mean opinion score, per ITU standards (1996), we opted to describe comparison mean opinion score results using the term “Sound Quality Ratings.”

There were 25 trials in each experiment. Subjects were given verbal instructions, along with a live demonstration of the software interface functionality on the computer, and then were required to complete a practice round supervised by the researcher. The subject was responsible for switching between programs using the FineTuner remote control. The instructions were: (1) Click “Play” to listen to the music clip. You may replay the music clip as often as you wish. (2) Move the program 1 slider to “Same as Prog 1” (i.e., the midpoint of the scale). (3) Switch the CI processor to program 2 using the remote control. (4) Play the music clip and move the program 2 slider to rate the sound quality as it compares to program 1. (5) Switch the CI processor back to program 1 and listen to the music clip again. (6) Repeat steps (3) and (4) for program 3. (7) Click “Save and proceed” when you are satisfied with your ratings of programs 2 and 3 as compared to program 1. This procedure enabled a subject to express whether the experimental program(s) provided better or worse sound quality than the clinical default settings, and to what degree.

During the practice round, the subjects were required to complete the task for at least three trials (music clips), but were allowed to do additional trials until they reported they were comfortable using the computer, interacting with the software interface, and using the FineTuner remote control. To ensure the programs were changed correctly, the researcher enabled the indicator light on the processor and observed the number of light flashes to verify that they corresponded with the intended program change. During a practice round, subjects used whichever programs they were going to use for the following experiment. Each experiment took an average of 30 to 60 minutes per ear. The CI recipient was given a break between ears (for the bilateral subjects) and between Experiments No. 1 and No. 2 (to allow for device reprogramming and to rest).

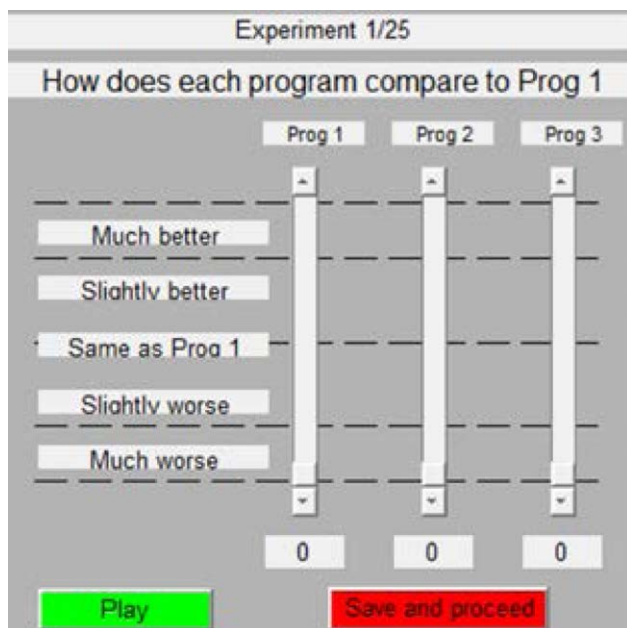


Fig. 3. Screenshot of the test interface. Participants were asked to compare the relative sound quality of three cochlear implant programs on a sliding scale while listening to a real-world musical clip.

## Statistical Analyses

All statistical analyses were completed using the R statistical computing program (R Core Team 2020). A linear mixed effects (LME) approach was applied using the “lme4” package (Bates et al. 2015). For specific models and factors, see results below. To test for significant differences between test conditions within a single ear, comparisons were made with pairwise t-tests (paired, 2-tailed) and Bonferroni correction were applied.

## RESULTS

### Experiment No. 1: Maplaw

We used an LME approach where the initial model had a single fixed factor: *Maplaw*, and no random factor. Noting that there was a large variability among the 17 CI ears tested (14 participants, three of whom were tested on both sides), we first considered a random intercept with the random factor *Ear* being nested within *Participant*. A likelihood ratio test compared the initial model against this more complex model: it accounted for significantly more variance [ $\chi^2(1) = 20.2$ ,  $p < 0.001$ ]. Next, we considered random slopes for the effect of *Maplaw* and the model improved further [ $\chi^2(5) = 259.9$ ,  $p < 0.001$ ]. On the other hand, random intercepts by test *Item* (i.e., 25 different musical excerpts) did not improve the model, even before including *Ear:Participant* [ $\chi^2(1) = 0.1$ ,  $p = 0.713$ ], nor did random slopes for the effect of *Maplaw* by *Item* [ $\chi^2(6) = 4.3$ ,  $p = 0.632$ ]. Thus, the final model of this first analysis was of the form: “Score ~ Maplaw + (1 + Maplaw | Ear:Participant)” and compared to a null model without Maplaw as fixed factor, to reveal a significant main effect of Maplaw [ $\chi^2(2) = 11.8$ ,  $p = 0.003$ ] (Bates et al. 2015). The LME notation above simply states that the dependent variable *Score* varies as a function of the experimental factor, but that there are additional variables (without direct relevance to the experimental design) accounting for some variance. The effect of the program with Maplaw of 2000 was estimated at 10.2 points above the default program ( $p = 0.003$ ), while the program with Maplaw of 500 was not significantly different than the default program ( $p = 0.278$ , with an estimate of −6.1 points). In summary, the experimental condition with Maplaw of 2000 was rated highest in sound quality by the group (with a mean score of  $110.2 \pm 4.7$ , 95% confidence interval), the Maplaw of 500 was rated lowest in sound quality ( $93.9 \pm 7.3$ ), with the default program (Maplaw of 1000) always fixed at 100, as seen in Figure 4. It is worth noting that the Maplaw of 2000 group average score of 110.2 falls in the “Slightly better” range and Maplaw of 500 group average score of 93.9 corresponds to the “Slightly worse” range. Additionally, while the “Raw” Sound Quality Scores ranged from 0 to 200, in several figures, including the left panel of Figure 4, the y axis displays “Normalized” sound quality scores, which range from −100 to 100. This was done so that the midpoint/default program is at 0 on the y axis, allowing for positive ratings to be above the x axis and negative ratings to be below the x axis. The linear adjustment to create “Normalized” scores consisted of subtracting 100 from all “Raw” scores.

The average sound quality scores of the programs with Maplaws of 500 and 2000 for each individual showed considerable intersubject and interaural variability, as seen in Figure 5. Bilateral CI subject No. 4, for example, trended toward a slight preference for music sound quality with a

Maplaw of 500 in the right ear ( $p = 0.064$ ), but in the left ear they had a distinct preference for a higher Maplaw of 2000 ( $p = 0.012$ ) and dislike for a lower Maplaw of 500 ( $p = 0.008$ ). In contrast, bilateral CI subject No. 7 preferred a Maplaw of 2000 compared to the default for each ear individually ( $p < 0.001$ ). On the whole, 53% of the CI ears (9 of 17) preferred a Maplaw of 2000 to the default 1000 ( $p < 0.025$ ), and the remaining 47% had ratings that were not significantly different. For the lower Maplaw of 500, ratings were better than the default 1000 for 12% of CI ears (2 of 17;  $p < 0.025$ ), worse for 41% (7 of 17;  $p < 0.025$ ), and not significantly different for the remaining 47%. Interestingly, subject 3L rated both the higher and lower Maplaws as better than the default ( $p < 0.001$  and  $p = 0.002$ , respectively), possibly indicating a placebo effect or general positive bias towards the experimental programs, but most other subjects were consistent in their judgments, that is, opposite appraisals for the two nondefault Maplaws (see also Panel A of Supplemental Digital Content 3, <http://links.lww.com/EANDH/A927>).

**Musical Genre** • Next, we looked at the effect of musical genre and whether it influenced the effect of *Maplaw*. Following a similar reasoning, we compared the previous model—that included *Maplaw* as a fixed factor and random intercepts and slopes by *Ear:Participant*—to a more complex model that had *Genre* as a second fixed factor, without and then with interaction term. There was a significant main effect of *Genre* [ $\chi^2(4) = 24.8$ ,  $p < 0.001$ ] and *Genre* interacted with *Maplaw* [ $\chi^2(8) = 16.3$ ,  $p = 0.038$ ]. To better understand the origin of this interaction, we performed pairwise comparisons. As illustrated in Figure 6, the program with Maplaw of 2000 was significantly better than the default program for Classical by 11.3 points

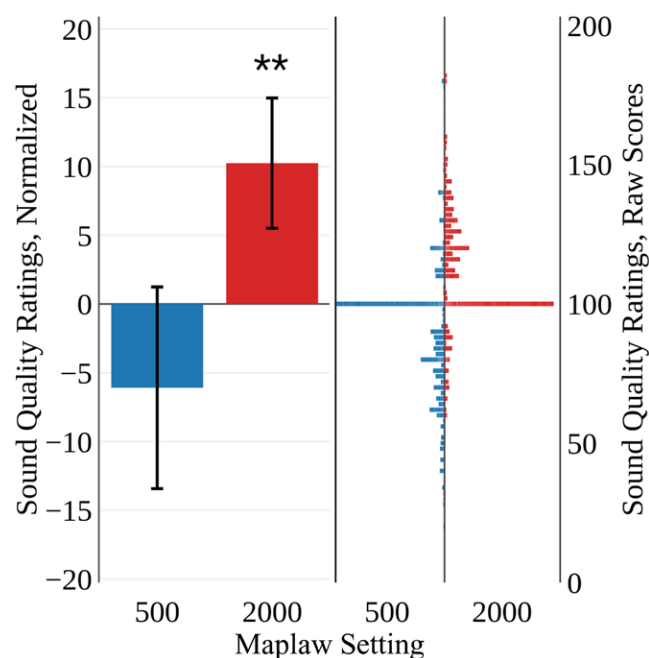


Fig. 4. Experiment No. 1—Group Results. Music sound quality ratings for the group when using Maplaws of 500 and 2000, as compared to Maplaw of 1000 (the default condition, fixed at 0 on the y axis). The vertical columns (on the left) represent the average across all subjects; error bars represent 95% confidence interval. \*\*The group average for Maplaw of 2000 was significantly different from the default condition ( $p < 0.01$ ). The horizontal bars in the histogram (on the right) display the distribution of raw scores.

( $p = 0.005$ ), Country by 11.0 points ( $p = 0.007$ ), and Jazz by 14.7 points ( $p < 0.001$ ), but did not reach significance for Hip-Hop ( $p = 0.088$ ) or Rock ( $p = 0.133$ ). The program with Maplaw of 500 was worse than the default program for Rock by 11.1 points ( $p = 0.050$ ), but did not reach significance for the others: Classical ( $p = 0.353$ ), Country ( $p = 0.238$ ), Hip-Hop ( $p = 0.189$ ), or Jazz ( $p = 0.856$ ).

Following on the effect of musical genre, we were particularly interested in examining how well genres with purely instrumentals versus vocals would be perceived. Thus, we reiterated an analysis by replacing *Genre* by *Mode* (with Instrumentals consisting of Classical and Jazz, and Vocals consisting of Country, Hip-Hop, and Rock). There was a main effect of *Mode* [ $\chi^2(1) = 14.9$ ,  $p < 0.001$ ] and a significant interaction [ $\chi^2(2) = 8.5$ ,  $p = 0.014$ ]. As illustrated in Figure 6, the program with Maplaw of 2000 outperformed the default by 13.0 and 8.4 points ( $p < 0.001$ , and  $p = 0.015$ , for instrumentals and vocals, respectively). The program with Maplaw of 500 did not differ from the default for either instrumentals ( $p = 0.883$ ) or vocals ( $p = 0.091$ ).

**Demographic Factors and Musical Training** • We reasoned that appreciation of musical excerpts might have much to do with experience with music in the first place. We plotted the random slopes (for the effect of *Maplaw* for each *Ear:Participant* combination, similarly to the analysis of CI-related factors) as a function of years of musical training. Curiously, as illustrated in Panels A and B in Supplemental Digital Content 2, <http://links.lww.com/EANDH/A926>, the differences between the experimental Maplaw programs (500 and 2000) tended to disappear with more musical training, although these are weak correlations ( $r = 0.5$ ,  $p = 0.043$  and  $r = -0.47$ ,  $p = 0.056$ , respectively).

Additionally, the differences were inversely related to one another ( $r = -0.64$ ,  $p = 0.006$ ), shown in Panel A in

Supplemental Digital Content 3, <http://links.lww.com/EANDH/A927>. This is an interesting finding: somehow, the users who would benefit most from the higher Maplaw program (2000) were also the ones most disliking the lower Maplaw program (500), and vice-versa (although all participants exhibited positive slope for the program 2000, that is, always better than the default program).

To explore whether other variables could somehow contribute to this relationship, a similar attempt was made with number of hours listening to music per week, but either slope failed to reach significance ( $p = 0.37$  and  $p = 0.63$ ) (not shown). A similar attempt was made with chronological age, but again, both failed ( $p = 0.83$  and  $p = 0.25$ , Panels C and D in Supplemental Digital Content 2, <http://links.lww.com/EANDH/A926>). Similar attempts were made with duration of CI use, onset of HL, and onset of severe-profound HL, without any success (Panels E through J in Supplemental Digital Content 2, <http://links.lww.com/EANDH/A926>).

Overall, therefore, the effect of musical training does not appear to be a byproduct of another variable covarying with it. In an attempt to turn this variable into a categorical one, we defined a cutoff of 4 years of training to split the cohort into two halves (below which one is considered “less musically trained”, and above which one is considered “more musically trained”). A repeated-measures ANOVA on random slope as a dependent variable with one between-subject factor (music training) and one within-subject factor (Maplaw) revealed a main effect of Maplaw [ $F(1,15) = 13.7$ ,  $p = 0.002$ ], no main effect of music training [ $F(1,15) = 2.5$ ,  $p = 0.133$ ], but a significant interaction [ $F(1,15) = 9.3$ ,  $p = 0.008$ ]. The results are illustrated in Supplemental Digital Content 4, <http://links.lww.com/EANDH/A928>, and suggest—in line with the correlation approach—that differences between Maplaw setting preference disappeared in the group with more musical training.

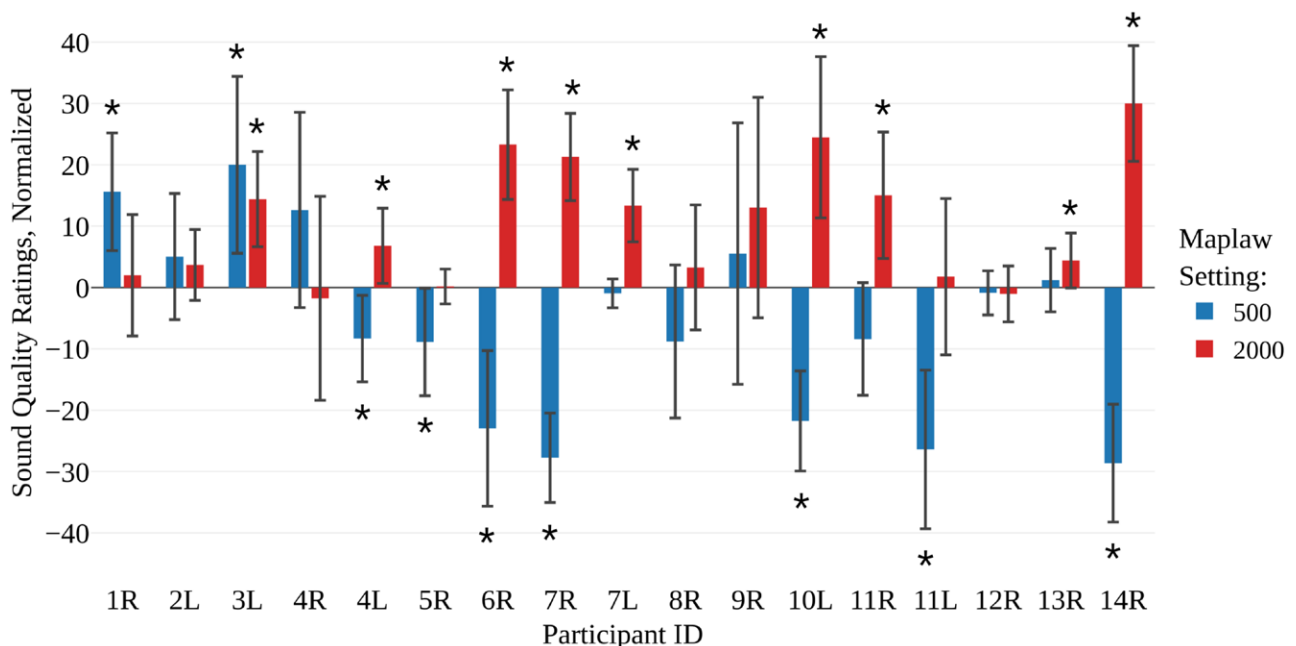


Fig. 5. Cochlear implant subjects' individual music sound quality ratings when using Maplaws of 500 and 2000, as compared to the Maplaw of 1000 (the default program, fixed at 0 on the y axis). Error bars represent 1 standard deviation from the mean. \*The corresponding column was significantly different from the default condition ( $p < 0.025$ ).

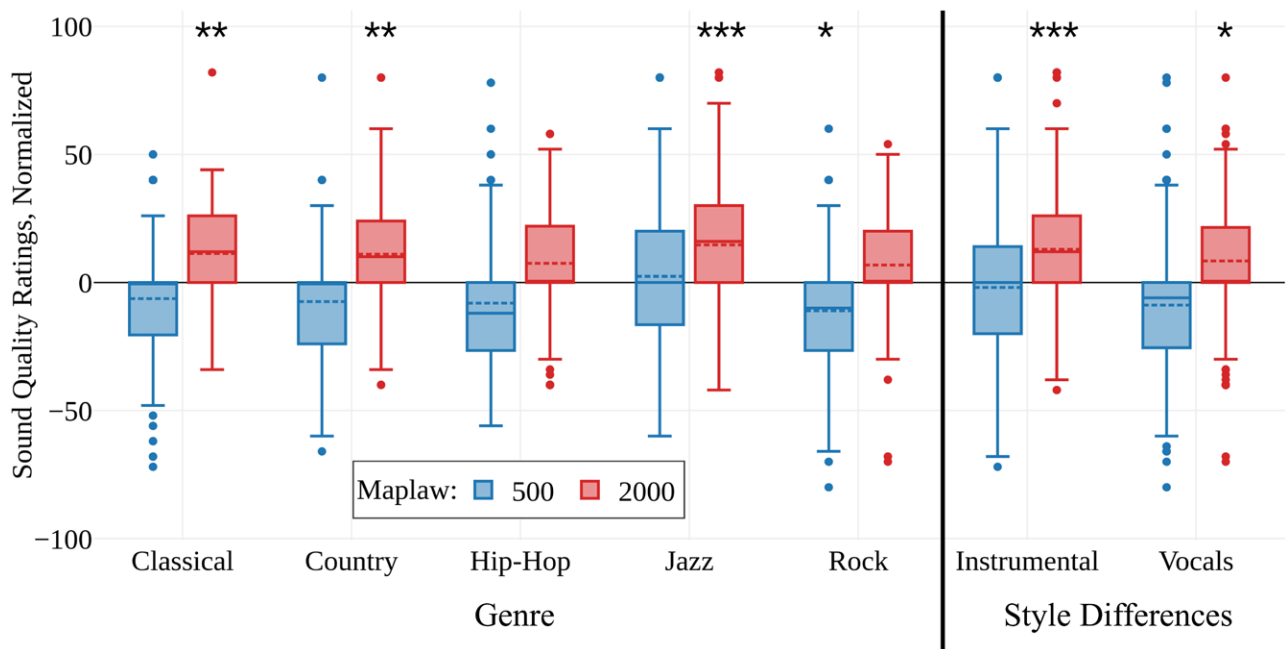


Fig. 6. Effect of Maplaw on sound quality ratings for musical genres and styles. The musical samples used in this study included five genres: Classical, Country, Hip-Hop, Jazz, and Rock. The Instrumental category includes Classical and Jazz, while the Vocals category combines the Country, Hip-Hop, and Rock music clips. \* $p < 0.05$ ; \*\* $p < 0.01$ ; \*\*\* $p < 0.001$ .

### Experiment No. 2: AGC

We used an LME approach where the initial model had a single fixed factor: *AGC*, and no random factor. Noting that there was a large variability among the 11 ears tested (10 participants, one of whom was tested in both ears), we first considered a random intercept with the random factor *Ear* being nested within *Participant*. A likelihood ratio test compared the initial model against this more complex model: it accounted for significantly more variance [ $\chi^2(1) = 59.9$ ,  $p < 0.001$ ]. Next, we considered random slopes for the effect of *AGC* and the model improved further [ $\chi^2(5) = 192.7$ ,  $p < 0.001$ ]. On the other hand, random intercepts by *Item* (i.e., 25 different musical excerpts) did not improve the model, even before including *Ear:Participant* [ $\chi^2(1) = 0.5$ ,  $p = 0.460$ ] nor did random slopes for the effect of *AGC* by *Item* [ $\chi^2(6) = 5.9$ ,  $p = 0.432$ ]. Thus, similar to Experiment No. 1, the final model was of the form: “Score  $\sim$  AGC + (1+AGC | Ear:Participant)” and compared to a null model without fixed factor it revealed a significant main effect of AGC [ $\chi^2(2) = 6.3$ ,  $p = 0.042$ ]. This key finding supports the idea that different compression ratios (than those used by default) can enhance music appreciation in CI users. It was, however, not a strong effect. Pairwise comparison between the 3.5:1 AGC relative to the default 3:1 AGC did not reach significance ( $p = 0.059$ , despite a 14.6 point difference). Comparison between the 2.5:1 AGC relative to the default AGC was also not significant ( $p = 0.546$ , with an estimate of 2.4 point difference). In other words, this main effect should be taken with caution, but, if anything, it was driven by the preference granted to a stronger compression.

To summarize, the AGC 3.5:1 program was rated higher overall in sound quality ( $114.6 \pm 10.7$ , 95% confidence interval) relative to the default. The program with an AGC of 2.5:1 was rated similarly to the default ( $102.4 \pm 3.9$ ). The average scores for the group are shown in Figure 7, which also includes

a histogram showing the frequency distribution of each score. It is notable that the vast majority of scores were at 100, labeled “Same as Prog 1” on the user interface.

Figure 8 displays the individual results for music sound quality between programs with various AGCs, and shows much less difference between programs for most subjects as compared to Experiment No. 1. Most of the significant difference in the group data for this cohort can be attributed to subjects No. 1L and No. 13R. There were three subjects, No. 1L, No. 8R and No. 14R, who consistently rated both experimental programs higher than the default—which is counterintuitive and may point to a placebo effect, that is, the belief that any of the experimental programs was supposed to be an improvement on their current perception of music.

**Additional Factors** • Please refer to the Supplementary Data Analysis in Supplemental Digital Content 9, <http://links.lww.com/EANDH/A924> and Figures 1–8 in Supplemental Digital Content 1–8, <http://links.lww.com/EANDH/A925>; <http://links.lww.com/EANDH/A926>; <http://links.lww.com/EANDH/A927>; <http://links.lww.com/EANDH/A928>; <http://links.lww.com/EANDH/A929>; <http://links.lww.com/EANDH/A930>; <http://links.lww.com/EANDH/A931>; <http://links.lww.com/EANDH/A932> for more detail on the impact of musical genre, CI-related factors, musical training, etc. None of the additional factors tested were found to be statistically significant in predicting music sound quality scores of Maplaw or AGC programs. Our statistical analysis did not reveal what (if any) demographic factors subjects No. 1L and No. 13R may have had in common that resulted in their preference for a higher AGC ratio.

### DISCUSSION

In this study, we examined the impact of changing Maplaw and AGC settings on music sound quality ratings in MED-EL CI users. Previous studies have looked at the impact of DR

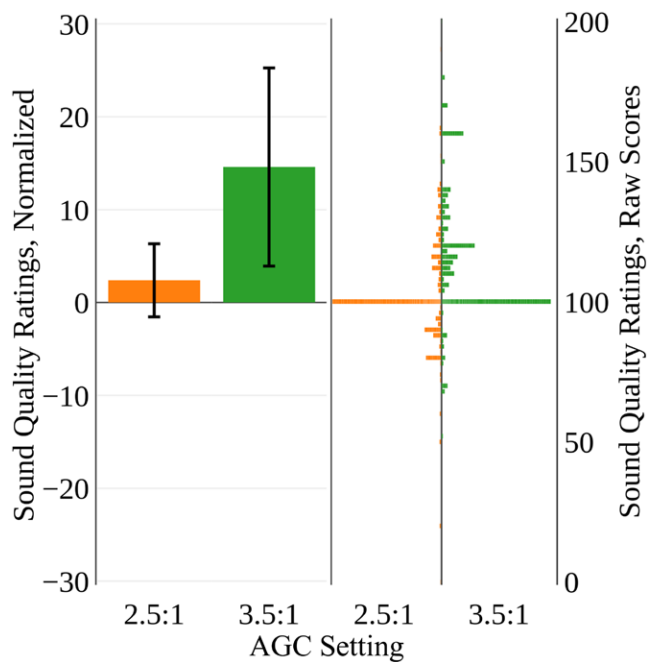


Fig. 7. Experiment No.2—group results. Music sound quality ratings for programs with automatic gain control (AGC) settings of 2.5:1 and 3.5:1, as compared to AGC of 3:1 (the default condition, fixed at 0 on the y axis). The vertical columns (on the left) represent the average across all subjects; error bars represent 95% confidence interval. The horizontal bars in the histogram (on the right) display the distribution of raw scores.

compression parameters on speech recognition in CI users. Fu and Shannon (1998) studied the effects of varying levels of compression applied to the signal processing in Cochlear Corp. N22 devices, and found that NH listeners perform best with a linear function while CI users perform best with an exponential loudness growth function that restored loudness linearity.

In follow-up studies in a small sample of users ( $n = 3$ ), Fu and Shannon (1998, 1999a,b) found that strongly compressive amplitude functions were worse than weakly compressive mapping functions for speech recognition in high levels of noise, although it should be noted that results may differ for other CI brands.

Loizou et al. (2000) examined the effect of varying the level of logarithmic compression on speech recognition in CI users. The investigators found that near-linear amplitude mapping yielded poorer speech recognition in quiet than compressive power functions, but the degree of compression was not significant.

Boyd (2006) examined the effects of compression settings in MED-EL users on speech recognition and found that more compression (Maplaws: 500 and 1000) resulted in better detection of soft sounds than lower compression settings (Maplaws: Linear (0) and 100). The largest difference in acoustic detection thresholds was seen between Maplaws of 100 and 500 (~7 dB), and there was a negligible change between 500 and 1000 (~1 dB). A study by Boyd and Euthymiades (2009) investigated the impact of Maplaw settings on speech quality and loudness by allowing CI users to adjust the Maplaw while listening to speech stimuli. Results indicated that for an average intensity level of conversational speech, there is a wide range of preferred Maplaw settings to achieve optimum comfort and sound quality, albeit all with some degree of compression applied (Maplaw range: 10–2000).

There appeared to be very limited literature regarding optimizing AGC parameters. In 1999, Stöbich et al. found that a dual-loop AGC was more beneficial than a single fast AGC, and that between a 3:1 and a 6:1 compression ratio; the 3:1 was more advantageous for recognition of loud speech in quiet.

Taken together, the described studies above have explored different intensity mapping functions for speech recognition in quiet and in noise, as well as listener preferences. They are

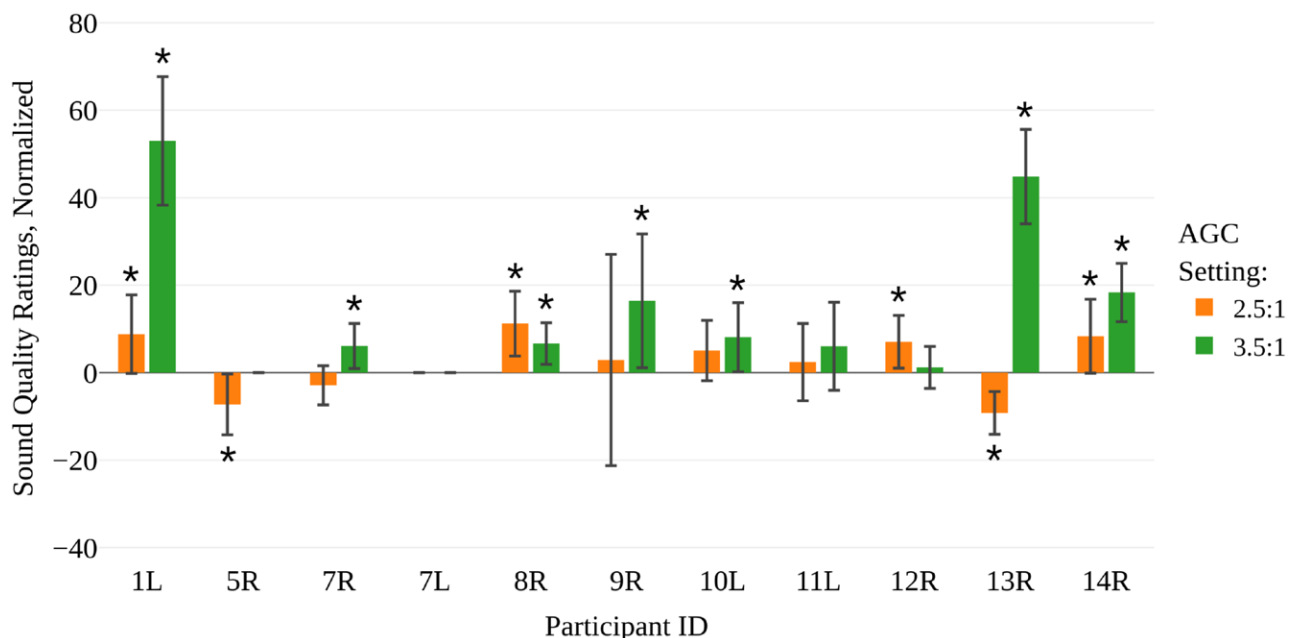


Fig. 8. Individual subjects' ratings of music sound quality for AGC settings of 2.5:1 and 3.5:1, as compared to the default AGC of 3:1 (fixed at 0 on the y axis). Of note, subject 7L could not detect a difference between the programs with different AGCs and hence has an average of  $0 \pm 0$  for both programs. Error bars represent 1 standard deviation from the mean. \*The corresponding column was significantly different from the default condition.

consistent with the finding that some level of logarithmic compression is needed (and preferred) for optimum speech recognition at average intensity levels and for audibility of soft sounds. The hypothesis of the current study was that CI subjects would prefer less compression than the default setting (i.e., Maplaw of 1000, AGC of 3:1), to increase and possibly better appreciate the amplitude modulation depth of the music samples. The results of the study, however, indicate that CI users prefer higher than default compression settings for recorded commercial music, a finding which is also reported in the literature for music appreciation by NH listeners (Vickers 2011; Taylor & Martens 2014; Taylor 2015). The CI users reported improvements in music sound quality with a higher Maplaw setting (2000) than the clinical default (1000). There was, however, considerable variability both within and between subjects regarding which Maplaw setting was preferred. Subjective feedback from subjects regarding higher Maplaw settings indicated better audibility for lyrics and softer instruments; typical comments included “more full,” “punchier,” “vibrant,” etc. During the test sessions, we observed that the CI listeners typically expressed a clear preference for one Maplaw setting over another, but that they could not tell the difference between AGC programs for music listening.

We did observe a trend toward preference for a higher AGC setting (3.5:1) over the clinical default (3:1), although this trend was driven primarily by just two subjects and should be interpreted with caution. Additionally, the comparison between programs with different AGCs was made using a Maplaw of 1000. It is possible that, when the Maplaw is 1000, the effects of AGC ratios are limited, and using a lower Maplaw (e.g., <500) would have accentuated the impact of changes to the AGC ratios on perception of acoustic stimuli. We opted to fix Maplaw at a value of 1000, a common clinical default setting, to make the results applicable to the most common clinical scenarios encountered in practice. We decided not to examine the interaction between simultaneous manipulation of both AGC and Maplaw since it was beyond the scope of the present study and would have made the experiment significantly longer. Investigation of this interaction, and with greater numbers of subjects, would be an important topic for further study. Another area of future study would be investigation of preferred compression settings for various intensity levels of music. It is possible that the lack of significant impact of AGC was a function of the presentation level of the stimuli. It should be noted that these Maplaw and AGC findings apply specifically to MED-EL CIs, and other CI brands have parameters that handle compression differently, and as such these results are not generalizable to all CI devices.

Since people listen to music in a wide variety of situations (e.g., in a quiet room, at a live concert, in the car listening to the radio, etc.), these results likely do not apply in all listening situations. For example, in the case of a higher Maplaw, which improves audibility for soft sounds, that change may be preferable for listening to music in a quiet room but be detrimental in a vehicle due to interference from road noise. One limitation of the study was that the interaction between compression settings and other automatic sound management features (i.e., noise reduction algorithm and directional microphone mode) was not investigated. It is possible that having these sound management features enabled may alter the findings of the study, and this interaction is a potential area for future research.

Contrary to common clinical thought that using DR compression settings that are as linear as possible is optimal for

music listening, as with hearing aids, our results suggest that CI programming for electric hearing needs to be treated differently than is hearing aid programming for acoustic hearing due to DR differences (Chasin & Russo 2004; Chasin 2012; Croghan et al. 2014). The root cause of the difference in compression ratio preference for music between electric and acoustic listening is unclear. It is possible our findings are due in part to the underlying damage to the auditory system that led to the ear receiving a CI in the first place. Whether the difference in compression ratio preference is due to a degraded auditory system or the mechanism of electrical listening is beyond the scope of this article. What is clear is that there is a difference in DR perception of CI listeners as compared to NH, as exemplified by the difference in electric and acoustic DR, both total DR and also discriminable step size resolution (Zeng 2004).

One potential clinical application of the findings of the present study is that when an audiologist is creating a program specifically for music listening, it may be beneficial to the patient to use a program with a higher Maplaw (i.e., 2000). This would increase audibility for softer instruments and/or lyrics in the music. It may be necessary to also decrease MCLs globally to compensate for an overall upward shift in loudness from the higher Maplaw. The effects on speech recognition tests were not specifically assessed using different Maplaw settings.

Spahr and Dorman (2005) examined the effects of minimum stimulation levels (THR<sub>s</sub>) in MED-EL signal processing. They found no difference between mean speech recognition abilities for CI users when THR<sub>s</sub> were set to 0 and when they were set at 10% or at measured levels. This was true for both soft speech in quiet and average speech with +10 dB SNR background noise. Setting THR<sub>s</sub> to measured thresholds provided better audibility for soft sounds (on average 9 dB for soft sounds as compared to THR<sub>s</sub> set to 0). Boyd (2006) examined the effects of THR<sub>s</sub> and Maplaw settings on speech recognition and acoustic thresholds. They found that the setting of measured THR<sub>s</sub>, while not statistically significant, did trend ( $p \sim 0.06$ ) toward improving acoustic thresholds, as compared to using minimum THR<sub>s</sub>. The setting of THR<sub>s</sub> did not have an impact on speech recognition at an average conversational level. For our experiment, we opted to use a variety of common clinical settings for THR levels: 0, 10% of MCL, and measured THR<sub>s</sub>. We did not see an effect of THR settings on Maplaw or AGC results, although the effect would have to be quite large to become apparent in our small sample size (Supplementary Data Analysis in Supplemental Digital Content 9, <http://links.lww.com/EANDH/A924> and Supplemental Digital Content 1 and 7, <http://links.lww.com/EANDH/A925>; <http://links.lww.com/EANDH/A931>). Thus, our study's findings do not contradict the prior research on THR level settings by Spahr and Dorman (2005) and Boyd (2006).

We did find a possible placebo effect for preference for the experimental programs (some subjects had higher preference for both lower and stronger compression than the default). This is something to consider when doing this type of study; however, it is unlikely to negate the significance of the study findings with regards to higher preference for stronger compression levels because: (1) it did not favor one manipulation over another (strong versus weak compression) and (2) it was not consistent across the two experiments in any given subject.

In this study, each ear was tested individually, although we know that in day-to-day life many CI recipients listen to

music with two ears. There was no clear pattern for the bilateral subjects in our cohort, and some had a different preference for each ear. Due to time constraints we did not obtain any bilateral test data, although it would be interesting for future research to explore how the compression setting preferences obtained in the unilateral condition compare to those for bilateral, bimodal, and single-sided deafness CI users. We know that at least a subset of patients within these groups benefits from binaural summation, which is the effect of a sound being perceived as louder when it is heard with two ears versus just one ear. It also would be interesting to see if the preferences that we found in this study for a higher Maplaw and AGC while listening unilaterally would be increased, unchanged, or decreased by the binaural summation that occurs when listening bilaterally. Furthermore, exploring the intersection of hearing aid and CI compression settings in subjects who use both types of devices, such as electroacoustic CI devices or use of a hearing aid in the ear contralateral to the CI could yield greater insight in our findings.

Another area for future study is the use of single instruments to study compression setting preferences. Perhaps, the complexity in this set of musical stimuli, including the large number of competing instruments and vocals, reduced the prominence of the effect of compression on music sound quality. It is possible that using single instruments or other less complex stimuli may show a clearer preference among CI listeners.

## CONCLUSION

CI recipients preferred, on average, a higher than default Maplaw setting for music listening, with considerable inter-personal and interaural variability, suggesting that audiologists may want to offer their patients a few programs with alternate compression settings to compare the sound quality of music to that offered by default settings.

The differences in Experiment No. 2 were more subtle, and most test subjects could not detect a difference between the various AGC settings for music sound quality.

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M.L.G. designed the study, performed the experiments, analyzed the data, and prepared the manuscript. M.L.D.D. analyzed the data and contributed figures for the manuscript. P.J. designed the user interfaces for data collection and facilitated data analysis. K.C.B. assisted with manuscript preparation. C.J.L. designed the study, provided critical revision of the manuscript, and oversaw the study. All authors discussed the results and implications and commented on the manuscript.

Preliminary data from this project was presented at the annual meeting for the American Auditory Society, Scottsdale, AZ, March 1, 2019.

The data and materials that support the findings of this study are openly available in the Dryad data repository ([www.datadryad.org](http://www.datadryad.org)) at <https://doi.org/10.7272/Q6JH3JDB> (Gilbert 2020).

The authors have no conflicts of interest to disclose.

Address for correspondence: Melanie L. Gilbert, AuD, Department of Otolaryngology-Head & Neck Surgery, University of California, San Francisco, 2233 Post Street, 3rd Floor, Box 0342, San Francisco, CA 94115, USA. E-mail: [melanie.gilbert@ucsf.edu](mailto:melanie.gilbert@ucsf.edu)

## OPEN PRACTICES

This manuscript qualifies for an Open Data Badge and an Open Materials badge. The materials and data have been made publically available at <https://doi.org/10.7272/Q6JH3JDB>. More information about the Open Practices Badges can be found at <https://journals.lww.com/ear-hearing/pages/default.aspx>. Received August 3, 2020; accepted September 8, 2021

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