Parameter-specific Morphing Reveals Contributions of Timbre and F0 Cues to the Perception of Voice Gender and Age in Cochlear Implant Users

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VOICE GENDER AND AGE PERCEPTION IN CI USERS

Purpose: Using naturalistic synthesized speech, we determined the relative importance of acoustic cues in voice gender and vocal age perception in Cochlear Implant (CI) users.

Method: We investigated 28 CI users' abilities to utilize fundamental frequency (F0) and timbre in perceiving voice gender (Experiment 1) and vocal age (Experiment 2). Parameter-specific voice morphing (TANDEM-STRAIGHT) was used to control acoustic cues in voice stimuli. Individual differences in CI users' performance were captured by quantifying deviations from mean performance of 19 normal hearing (NH) listeners.

Results: CI users' gender perception seemed exclusively based on F0, whereas NH listeners efficiently used timbre. For age perception, timbre was more informative than F0 for both groups, with minor contributions of temporal cues. While a few CI users performed comparable to NH listeners overall, others were at chance. Separate analyses confirmed that even in high performing CI users, gender perception was almost exclusively based on F0. While high performers could discriminate age in male and female voices, low performers were close to chance overall, but used F0 as misleading cue to age (classifying female voices as young and male voices as old). Satisfaction with CI generally correlated with performance.

Conclusions: We confirmed that CI user gender classification bases mainly on F0, but high performers could make reasonable usage of timbre cues in both gender and age perception. Overall, parameter-specific morphing is a promising approach to objectively assess individual profiles of CI users' abilities to perceive nonverbal social-communicative vocal signals.

Keywords (max. 5): parameter-specific voice morphing; cochlear implant; voice gender; vocal age; timbre

Introduction

Cochlear implants (CIs) are sensory prostheses allowing individuals with severe sensorineural hearing loss to perceive sound by directly stimulating the auditory nerve. While CI technology has advanced in the last decade, significant limitations to complex sound perception remain (Caldwell, Jiam, & Limb, 2017). Importantly, while auditory-only speech understanding has been the primary goal of CI technology (Peterson, Pisoni, & Miyamoto, 2010), other nonverbal aspects of hearing contribute substantially to perceived quality of life (QoL). Schorr, Roth, and Fox (2009), for instance, reported that CI users' perceived QoL was correlated with accurate identification of non-linguistic emotional sounds, but not with word recognition as assessed by the Lexical Neighborhood Test (Kirk, Pisoni, & Osberger, 1995). Indeed, the perception of nonverbal voice signals is important to successful human communication, as voices deliver rich information related to speaker gender, age, identity, emotional state or health (Schweinberger, Kawahara, Simpson, Zäske, & Skuk, 2014).

Most studies investigating voice perception in CI users found general deficits – sometimes with substantial individual differences – in the ability to perceive voice gender (e.g., Fu, Chinchilla, & Galvin, 2004; Fu, Chinchilla, Nogaki, & Galvin, 2005; Fuller et al., 2014; Gaudrain & Baskent, 2018; Hazrati, Ali, Hansen, & Tobey, 2015; Kovacic & Balaban, 2009, 2010; Li & Fu, 2011; Massida et al., 2013; Meister, Fursen, Streicher, Lang-Roth, & Walger, 2016; Meister, Landwehr, Pyschny, Walger, & von Wedel, 2009) or emotion (e.g., Agrawal et al., 2013; Jiam, Caldwell, Deroche, Chatterjee, & Limb, 2017; Kim & Yoon, 2018; Paquette et al., 2018; Schorr et al., 2009; Tinnemore, Zion, Kulkarni, & Chatterjee, 2018; Waaramaa, Kukkonen, Mykkanen, & Geneid, 2018). Few studies reported impairments in other aspects of voice perception, such as speaker familiarity or identity (e.g., Gonzalez & Oliver, 2005; Muhler, Ziese, & Verhey, 2017;

Vongphoe & Zeng, 2005). To the best of our knowledge, the perception of vocal age cues in CI users has not yet been investigated, despite their relevance for social judgments (Montepare & Zebrowitz, 1998).

CI Technology

A main limiter of CIs is the small number of frequency channels (e.g., Carroll & Zeng, 2007). Electrode arrays typically consist of 12 to 22 electrodes, but less are normally stimulated at a time to avoid channel interactions. Incoming sound is preprocessed to reduce noise and to amplify relevant frequencies for speech perception, before electrode stimulation patterns are determined by a CI coding strategy that also adapts the dynamic range for each electrode, reflecting individual frequency-dependent hearing loss (e.g., Thomas & Tripathi, 2014, for a review on music perception). These and other individual factors (including the position of the electrode array within the cochlea and the status of the auditory nerve and brain structures) also affect the resulting percept, thus making it difficult to predict the outcome of an implantation, and limiting comparisons between CI users within and across studies (Pisoni, Cleary, Geers, & Tobey, 1999). We here aim at using a parameter-specific morphing approach in order to capture individual CI users' ranges of abilities to utilize different acoustic cues in two tasks that focus on the perception of nonverbal information in voices.

Pitch and Timbre

Pitch and timbre, together with loudness, are main attributes characterizing voice quality. While loudness relates to (frequency-dependent) perception of sound pressure, pitch relates to the fundamental frequency (F0) or vocal fold vibration rate, which determines whether voice is perceived as “deeper” or “higher”. Male voices have lower F0 compared to female voices (Simpson, 2009). Perceived timbre is determined by “*features [which] include spectral power distribution, rate and depth of amplitude or frequency*

modulation” (Thomas & Tripathi, 2014). Put simply, timbre allows listeners to discriminate two sounds having the same pitch and loudness (Pijl & Schwarz, 1995). Timbre depends both on the actual anatomy of a person’s articulatory system (e.g., vocal tract length, VTL) and on how it is used (e.g., vocal tract configurations during articulation). While the relative position of the first three formants (frequency bands with enhanced spectral energy) is idiosyncratic for a certain vowel percept, the absolute position of formants may be more important for discriminating individual speakers or groups. Males, for instance, have longer VTLs than females, resulting in lower male formants which can serve as further cues to voice gender (Simpson, 2009). Finally, other aspects (e.g., increase of noise in breathy voices, or jitter and shimmer in unstable phonation) may also affect timbre.

During aging, F0, timbre, loudness, and speaking rate change in a systematic manner. F0 is highest during childhood, and develops the above described sexual dimorphism in puberty. Subsequently, F0 decreases in women during menopause, and increases in older men, attenuating sexual dimorphism in older age (see Linville, 1996, for a review). Further, higher jitter and shimmer levels can cause more hoarse timbre in old voices, and both higher F0 and amplitude variability can cause the percept of increased vocal tremor (cf. Linville, 1996). A decrease of both male and female F1 formant frequencies may also affect timbre (Reubold, Harrington, & Kleber, 2010), and women were suggested to exhibit more pronounced age-related vocal tract lengthening, causing more substantial lowering of formants (Linville & Rens, 2001). Age-related changes in perceived loudness are less consistent (Morris & Brown, 1994; Ryan, 1972) but loudness control may be reduced, perhaps due to hearing loss (Kreiman & Sidtis, 2011). Moreover, old speakers typically show lower speaking rates and more pauses (Kreiman & Sidtis, 2011). Taken together, while systematic differences in acoustic cues between male and

female (and young and old) voices allow normal hearers to easily perceive speaker gender and age, relatively little is known about how CI users can utilize these cues to perceive gender and age.

Perception of Voice Gender in NH and CI Users

To perceive speaker gender, normal hearers use both pitch and timbre cues to similar extents (Assmann, Dembling, & Nearey, 2006; Hillenbrand & Clark, 2009; Pernet & Belin, 2012; Skuk & Schweinberger, 2014; E. L. Smith, Grabowecky, & Suzuki, 2007), albeit the relative importance of pitch and timbre can vary depending on a number of factors (cf. Skuk, Dammann, & Schweinberger, 2015, for more details). Voice gender perception by CI users was studied with a variety of methods, but few focused on the relative importance of acoustical cues. Below we focus on studies in which CI users evaluated natural (sounding) voices as stimuli, as these arguably best approach what CI user hear in social interactions.

Kovacic and Balaban (2009) used natural voice recordings of 40 (20 female) speakers with overlapping frequency ranges to investigate gender perception in 41 juvenile CI users (mean age = 12.3 years). While recognition rates were above 80% for low (<138 Hz) and high (>163 Hz) pitched voices, they dropped substantially for the androgynous voices in between. In 14 CI users Massida et al. (2013) found similarly poor gender discrimination for androgynous voices on a male-female morph-continuum. They used STRAIGHT-based voice morphing (Kawahara, Masuda-Katsuse, & de Cheveigne, 1999) to create 11 versions of a single /had/- utterance on a male-female continuum. Importantly, they report a clear dissociation between speech recognition and gender perception skills and found no improvement in gender perception with CI experience. However, since their morphing approach modified all acoustic cues conjointly, the results do not inform about the relative importance of different cues in CI users.

To examine the relative role of F0 and VTL cues on gender perception in 19 CI users, Fuller et al. (2014) used STRAIGHT-based voice resynthesis to systematically manipulate F0 and VTL cues from a single female Dutch source speaker. In four different words they shifted F0 by 0, 3, 6, 9, and 12 semitones, and combined these with six different VTLs of 0, 4, 7, 14, 19, and 23% of the source VTL. Gender classification was almost exclusively based on F0, and authors concluded that poor VTL perception contributes to poorer performance in gender categorization overall. Similar conclusions were drawn from a study on 11 CI users by Gaudrain and Baskent (2018), using consonant-vowel utterances of the same female Dutch source speaker to determine the “just noticeable difference” in F0, VTL, and both cues in combination in adaptive testing. Finally, while the above studies used brief utterances, Meister et al. (2016) studied effects of F0 and VTL modification on four different types of utterances with varying phonetic variability. Using Praat (Boersma & Weenink, 2011) they manipulated F0, VTL, or both from utterances originally spoken by one female German speaker, and reported that the 16 CI users mainly relied on F0 rather than VTL. As a limitation, although authors stated that they “*avoided unnatural mismatching combinations*”, this may not have been the case for the F0- or VTL-only conditions, where “*manipulations of isolated F0 did not affect formant frequencies, and manipulations of isolated VTL cues did not affect F0*”. Thus, increasing modifications of F0 or VTL introduce increasingly more conflicting information, which is why their results allow only limited conclusions on the relative impact of F0 and VTL cues.

Taken together, the above three studies all highlight a major role of F0 for voice gender perception in CI users, with little or no contribution of VTL cues (Fuller et al., 2014; Gaudrain & Baskent, 2018; Meister et al., 2016). As an important limitation, they all used synthesized voices originating from one female source speaker only. Their

method of VTL shifts also neglects potential further relevant cues such as breathiness (Henton & Bladon, 1985), and produces less realistic female-to-male formant transformation. We therefore decided to use a more comprehensive parameter-specific voice morphing approach which applies non-uniform scaling factors to individual formant frequencies (Skuk & Schweinberger, 2014, for similar arguments).

Perception of Vocal Age in NH and CI Users

Normal hearing listeners can perceive the approximate age of speakers from voice samples alone, and morphing systematically alters perceived age (Zäske & Schweinberger, 2011). However, accuracies of precise age estimations depend on a number of factors and vary substantially between studies (Kreiman & Sidtis, 2011). To relate acoustic cues to perceived age, studies used correlational approaches. As a notable exception, (D. R. R. Smith & Patterson, 2005) evaluated effects of STRAIGHT-based F0 and VTL manipulations in vowels originating from /hVd/ (e.g., /had/, /heed/, /hood/) utterances from a single male speaker. Listeners rated perceived gender/age in a combined 4-alternative-forced-choice (AFC) task, with options for “boy”, “girl”, “man”, and “women”. Age classifications were found to depend on perceived gender (for related findings see also Schweinberger, Walther, Zäske, & Kovacs, 2011) and while both cues served as robust indicators of sex and age when in a normal range, listeners relied more on VTL information for unusual F0 and VTL combinations. As a qualification, VTL varied substantially from 7.8 cm to 22.2 cm, thus serving as a strong cue to body size. To the best of our knowledge, no studies on vocal age perception from voices by CI users have been published so far.

Aim of the Study

We aimed at reassessing the relative importance of F0 and timbre (including formants as cues to access VTL) for voice gender perception in CI users, while using a

parameter-specific morphing approach with natural-sounding voices and substantial numbers of speakers and listeners (Experiment 1). We also investigated, for the first time, vocal age perception based on F0, timbre and timing cues in CI users (Experiment 2). TANDEM-STRAIGHT (Kawahara, Morise, Banno, & Skuk, 2013; Kawahara & Skuk, 2018) was used to generate experimental stimuli with controlled F0, timbre, and timing information. As in prior studies (e.g., Skuk et al., 2015; Skuk & Schweinberger, 2014; Zäske & Schweinberger, 2011; Zäske, Skuk, Kaufmann, & Schweinberger, 2013), we morphed between voices of male and female, or young and old, speakers. We varied only the parameter of interest (F0, timbre, or timing), keeping the residual parameters constant at an intermediate morph level, and thus uninformative for the task. This allows computational isolation of the degree to which a specific acoustical cue is used in the categorization tasks (gender or age), irrespective of the fact that different cues may interact to create a perceptual impression. It also allows to estimate the relative importance of each cue relative to a baseline in which all parameters were morphed in combination.

Our second important aim was to quantify individual differences both in CI users' performance and CI satisfaction. Specifically, we devised a performance measure expressing deviations in individual listeners' abilities to perceive voice gender or vocal age relative to the results from a group of normal hearing listeners (cf. Fuller et al., 2014, for a similar approach). We hypothesized that better (i.e. closer to the normal pattern) performance is correlated with higher CI satisfaction, and potentially may relate to CI experience and shorter duration of deafness prior to implantation.

Method

Listeners

A total of 28 CI users (15 female, 15 with bilateral implants) aged between 12 and 85 years ($M = 59.5$, $SD = 19.7$, cf. Table 1 for further information) and a control group of

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19 (12 female) healthy listeners aged between 15 and 85 years ($M = 42.9$, $SD = 19.6$, reporting normal hearing without hearing aids) were recruited and tested between June and July 2015 in the Cochlear Implant Rehabilitation Centre Thuringia, Erfurt, Germany. All were native German speakers.

Inclusion criteria for CI users were predefined as follows: (1) Bilateral or unilateral implants, with severe to profound hearing loss in the non-implanted ear that is fitted with a conventional hearing aid. (2) No neurological or psychiatric disorders. (3) No other otologic disorders. (4) Complete understanding of experimental instructions. Data from one CI user (f114), who reported muscular dystrophy, were included in the statistical analyses. Data from both a control listener (m704) and a CI user (m801) originated from an initial test run. As both completed the experiment and no modifications were applied on the listening experiments later, their data were included in the analysis. Data from three additional CI users (f117, f106, m208) were incomplete and therefore not analyzed, due to a high error of omission rate ($>19\%$ missed trials in Experiment 1, 9% missed trials in Experiment 2) in one case, or a termination of the listening experiments after few trials in two cases.

All listeners gave written informed consent. The experiment was carried out in accordance with the Declaration of Helsinki and APA ethical standards, and was approved by the Ethics Committee of Jena University Hospital (Reference 4418/04/15).

Stimuli

Speakers.

Original voice recordings were taken from the Jena Speaker Set (Zäske, Skuk, Golle, & Schweinberger, 2019) a database of voice recordings of more than 120 male and female, young (18-25 years) and old (60-81 years) native German speakers. High-quality audio recordings were made in a quiet and semi-anechoic room using a Sennheiser MD

421-II Microphone, a pop protection, and a Zoom H4n audio interface (16-bit resolution, 44.1 kHz sampling rate).

For morphing of stimuli of the gender experiment, we selected eight (four female) speakers with a mean age of 21.5 ± 2.3 years based on previous work (Skuk et al., 2015) and used two vowel-consonant-vowel (VCV) syllables /aba/ and /igi/. For the age experiment, we selected eight young (4 female) speakers (mean perceived age of 28.6 ± 2.2 years) and eight (4 female) old speakers (mean perceived age of 68.9 ± 1.8 years) uttering the German sentence “Keine Antwort ist auch eine Antwort” (“No answer is an answer as well”). In both experiments two additional speaker pairs were used for practice trials only. Please refer to Supplemental Material Section 2 for more details.

Voice morphing.

TANDEM-STRAIGHT is a speech analysis, modification and resynthesis framework that decomposes speech signals into source- and filter information, allowing to morph between them to create high-quality synthesized and naturally sounding voices (Kawahara et al., 2013; Kawahara et al., 2008; Kawahara & Skuk, 2018). Signals are decomposed into three components, depending on time (t) and frequency (f): (1) a fundamental frequency trajectory $F_0(t)$, (2), a spectrographic representation $P_s(t,f)$, which is a smoothed envelope of short-term power spectral representation of periodic signals, and (3) an aperiodicity spectrogram $A(t,f)$, that is a map of the random (aperiodic) to the deterministic (periodic) power ratios in each frequency band (Kawahara, Estill, & Fujimura, 2001; Kawahara, Katayose, de Cheveigné, & Patterson, 1999).

Based on a manual time-frequency mapping of key features (e.g., onset, offsets, formant frequencies) in the spectrograms of two utterances, parameter specific-morphing (as used in Skuk & Schweinberger, 2014), allows us to morph selected parameters (either F_0 , P_s , A , t , or f) individually or in combination, between the two utterances, leading to

naturally sounding synthesized voices with controlled acoustics.

All morphed stimuli were root-mean-square normalized to 70 dB SPL using Praat. Refer to the Supplemental Material for an overview of the morph types and modified parameters (Suppl. Section 2.3), for acoustic analyses of morphed stimuli (Suppl. Sections 7 and 8) and example auditory stimuli (.wav files in a .zip) of both experiments.

Stimuli for Experiment 1 (Gender).

For Experiment 1, we varied the F0-contour, the timbre (TIMBRE), or both in combination (FULLcT) along each male-female continuum, keeping the residual parameters constant at the intermediate “androgynous” morph level (ML50)¹. TIMBRE represents a combination of TANDEM-STRAIGHT parameters aperiodicity (A), formant frequency (f), and spectrum level (Ps), which were previously shown to best reflect timbre (Skuk et al., 2015; Skuk & Schweinberger, 2014). As timing (t) was constant in F0- and TIMBRE-morphs, we kept timing constant in FULLcT morphs as well.

Morph continua were generated from 0% to 100% femaleness in steps of 20%, resulting in 144 voice morphs (4 speaker pairs x 2 VCVs x 3 morph types x 6 morph levels). Additionally, we included 8 (4 speaker pairs x 2 VCVs) androgynous voices, with all parameters set to ML50, resulting in a total of 152 gender stimuli. Their mean duration was 682.6 ms ($SD = 58.7$, range: 607.8 – 814.9, $N = 152$), including 50 ms silence before onset and after offset.

Stimuli for Experiment 2 (Age).

For Experiment 2, we varied F0, TIMBRE, t (TIME), or, all parameters (FULL) along each young-old continuum, keeping any residual parameters constant at the

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¹ Note that morph level (ML) x refers to an interpolation of $x\%$ of the original female (or old) and $100-x\%$ of the original male (or young) utterance, with $0 \leq x \leq 100$.

intermediate morph level (ML50). Here we used only the extreme morph levels 0 (young) and 100 (old), resulting in 64 voice morphs (2 gender x 4 speaker pairs x 4 morph types x 2 morph levels). Additionally, we included eight age-ambiguous voices (one per speaker pair), with all parameters set at ML50, resulting in a total of 72 age-stimuli. Their mean duration was 2556.2 ms ($SD = 189.3$, range: 2033.7-3065.5, $N = 72$), including 100 ms silence before onset and after offset. Note that longer stimuli (sentences) were used in the age experiment (a) because we considered that these would reveal temporal cues, which could relatively be informative for age perception as discussed above, and (b) because vocal age perception is a relatively more difficult task. Supplemental Material Section 8 illustrates that our stimuli showed expected acoustic changes with respect to F0 and timing: Female (male) F0 slightly decreased (increased) with age in both the F0- and the Full-morphs, and old voices were longer in duration compared to young voices.

Design and Procedure

Questionnaires and General Procedure

Prior to the experiments (programmed with E-Prime® 2.0, Schneider, Eschman, & Zuccolotto, 2002) listeners completed a written self-report questionnaire on demographic characteristics. CI users additionally provided information about individual hearing history and answered a question for general satisfaction with the CI in everyday life situations (with response options “fully satisfied”, “satisfied”, “less satisfied”, and “not at all satisfied”, coded from 3 to 0, respectively). We also assessed relevant technical characteristics of CIs.

The order of experiments was fixed (Experiment 1 and, after a short break, Experiment 2). Participants were instructed to attentively listen to the voices, and to answer intuitively and as fast as possible. CI users were tested with the implant(s) alone, using their everyday processor(s). Unilateral CI users turned off their contralateral hearing

aid during the listening experiments. All further experimental instructions were presented in writing on a monitor. The entire test session lasted approximately 60 minutes and was supervised by a female experimenter.

Experimental setting.

Listeners were individually tested in an audiological test booth (~4 m²) of the Cochlear Implant Rehabilitation Centre Thuringia. They sat on a comfortable chair at 1 m distance in front of a monitor. Experimental stimuli were presented binaurally via two calibrated JBL Control-One loudspeakers at 70 dB SPL, at listeners' ear level and at approximately 1 m distance. After the presentation of each voice, listeners were instructed to perform a 2-AFC task and press one of two assigned keys on a response pad; key assignment was counterbalanced across listeners. A cardboard below the computer screen served as a constant reminder of the key assignment.

Procedure of Experiment 1 (Gender).

In Experiment 1, listeners had response options for "female" and "male". The experiment started with ten practice trials to acquaint listeners with the procedure. Practice stimuli came from two different male-female speaker pairs (one each uttering /aba/ and /igi/, respectively) that were not used in the main experiment. After practice, listeners could ask questions. If needed, the practice block was repeated. The main experiment consisted of 8 blocks with 19 test trials each. Individual breaks were allowed after each block.

A trial started with a black screen for 800 ms. After this, a green question mark centered on a black screen appeared; after another 200 ms, the test voice was presented. Test voices were presented in randomized order. Listeners' responses were recorded from test voice onset until 3000 ms following voice offset. A response closed the response window, and triggered the next trial slide immediately after voice offset. If listeners failed

to respond (error of omission) within this time window, the next trial slide comprised the sentence “Bitte reagieren Sie schneller” (“Please respond faster”) for 500 ms; otherwise a black slide was shown instead. No feedback was given otherwise. Participants categorized voice gender by pressing the corresponding key on the response pad. Mean duration of Experiment 1 (including practice trials and breaks) was approximately 11.2 minutes ($SD = 3.0$, range: 7.5 to 17.6, $N = 19$) for NH listeners, and 11.3 minutes ($SD = 3.2$, range: 6.9 to 22.3, $N = 28$) for CI users.

Procedure of Experiment 2 (Age).

In Experiment 2, listeners had response options for “young” and “old”, which was explained to refer to “younger than 50 years of age” (<50) and “older than 50 years of age” (>50), respectively. A total of 144 test trials with randomized order resulted from the fact that each of the 72 voices was presented twice. The experiment started with nine practice stimuli from different speaker pairs (one male, one female) that were not used thereafter. The main experiment consisted of 8 blocks with 18 test trials each. All other aspects of the procedure were analogous to Experiment 1. Mean duration of Experiment 2 including practice and breaks was 14.1 minutes for the NH listeners ($SD = 2.7$, range: 11.1 to 19.2, $N = 19$), and 13.5 minutes for the CI users ($SD = 2.2$, range: 11.1 to 19.8, $N = 28$).

Results

Statistical Analysis

Statistical analyses were conducted using R. Analysis of variances (ANOVAs) used the ezANOVA function from the ez-package with type-3 sums of squares. Where appropriate, we report epsilon corrections for heterogeneity of covariances (Huynh & Feldt, 1976), and Bonferroni corrections for multiple comparisons.

Performance Group Analysis

We initially performed ANOVAs with one factor of listener group (LGroup), comparing the NH listeners to the CI users. As we anticipated substantial individual differences in performance among CI users, we formally analyzed such differences by subdividing, for each experiment, the CI group into subgroups of “high” vs. “low” performers, using a median split procedure. To achieve this, we calculated a performance measure for each CI user and experiment. The difference score d captures the difference to the average NH listeners’ performance, similar to Fuller et al. (2014), where lower d reflects higher (closer to NH) performance.

To obtain the NH average, we initially calculated, for each stimulus k of the n experimental stimuli the mean proportion of female (or “>50”) responses across all NH listeners ($STIM_{kNH}$). We then calculated the difference score d_i for each CI user i as follows:

$$d_i = \left(\sum_{k=1}^n (|STIM_{kNH} - STIM_{ki}|) \right) / n$$

where $STIM_{ki}$ is 1 if CI user i classified a stimulus k as female (“>50”), and 0 for male (“<50”) otherwise.

Per experiment, the median split based on the difference scores (d_{gender} or d_{age} , across all morph types and stimuli) resulted in two CI groups ($n = 14$ each) of “high performers” with smaller d and “low performers” with larger d , respectively. We additionally calculated difference scores separately for each morph type (i.e., $d_{genderFullcT}$, d_{gender_F0} , and $d_{genderTIMBRE}$ in Exp. 1, and $d_{ageFull}$, d_{age_F0} , $d_{ageTIMBRE}$, and $d_{ageTIME}$ in Exp. 2).

Experiment 1 (Gender)

Trials either without key press within the time window (errors of omission, $N = 150$) or with reaction times < 200 ms (anticipatory responses, $N = 7$) occurred in only 2.2% of

all experimental trials, and were excluded from the analyses. Participants missed on average 3.3 trials ($SD = 3.6$, range: 0-13).

Initial analysis (all CI users).

Data was averaged across speaker pairs and analyzed by an initial $3 \times 2 \times 6 \times 2 \times 2$ mixed ANOVA on the proportion of “female” responses with the factors morph type (MType: F0, FULLcT, TIMBRE), VCV (/aba/, /igi/), morph level (ML: 0, 20, 40, 60, 80, 100) and two between-subject factors listener sex (LSex: male, female) and listener group (LGroup: NH group, CI group). Note that as we were not particularly interested in effects of VCV, reports of effects and interactions involving VCV only appear in Table 2 and Supplemental Material Section 3.

The initial ANOVA did not reveal a main effect or any interaction involving LSex ($ps \geq .083$). A subsequent ANOVA was therefore performed without factor LSex (for summary see Table 2). This analysis revealed a main effect of ML, which validated the voice morphing procedure. Further several two- and three-way interactions involving LGroup indicated substantial differences between the groups. The interaction LGroup x ML simply reflected steeper classification functions, and thus better performance overall, in NH participants compared to the CI users. The interaction LGroup x MType x ML, indicates prominent differences between NH and CI users (Figure 1) that were post hoc tested by two separate (one per group) 3×6 repeated-measure ANOVAs with the factors MType and ML. (cf. Table 2 for ANOVA results and Table 3 for descriptive statistics).

-Please insert Figure 1 about here-

NH listeners.

For the NH listeners, the 3×6 ANOVA revealed main effects of both MType and ML that were qualified by an interaction (Figure 1a). We post hoc tested the interaction of MType x ML, by running six separate ANOVAs, one for each ML with the factor MType.

The main effect of MType was significant for ML20 to 100, $F_{s(2,36)} \geq 8.7$, $ps \leq .001$, $\eta^2p \geq .3$, with a trend at ML0, $F(2,36) = 2.659$, $p = .084$, $\eta^2p = .129$.

Post hoc pairwise comparisons for each ML revealed significant differences between FULLcT and F0 for ML20 to ML100, $|ts(18)| \geq 3.536$, $ps \leq .007$, but not for ML0, $|t(18)| = 2.051$, $p = .170$, and between FULLcT and TIMBRE for ML20 to ML80, $|ts(18)| \geq 2.916$, $ps \leq .028$, but not for ML0 and ML100, $|ts(18)| \leq 1.863$, $ps \geq .236$. Comparing F0 and TIMBRE, while no significant differences were found for ML0 to ML60, $|ts(18)| \leq 1.568$, $ps \geq .403$, for ML80 and ML100 listeners were more likely to classify the TIMBRE stimuli as “female”, when compared to F0, $|ts(18)| \geq 2.807$, $ps \leq .035$. Overall, this pattern indicates more efficient gender classification of TIMBRE stimuli than F0 stimuli, at the female end of the morph-continuum.

All CI users.

For CI users, an analogous ANOVA revealed a main effect of ML, no main effect of MType, and an interaction between MType x ML (Figure 1b). As for the NH, we ran separate 3 x 6 ANOVAs with factor MType, separately per ML. This analysis revealed a significant main effect of MType for morph levels 0, 20, 80, and 100, $F_{s(2, 54)} \geq 4.143$, $ps \leq .021$, $\epsilon HF \leq .815$, $\eta^2p \geq .133$, but not for the two most ambiguous ML40 and ML60, $F_{s(2, 54)} \leq 2.202$, $ps \geq .120$, $\eta^2p \leq .075$.

Remarkably, Figure 1b shows virtually identical efficiency of gender classification for F0 and FullcT morphs. There were no significant differences between FULLcT and F0 for any ML, $|ts(27)| \leq 1.637$, $ps \geq .340$. By contrast, Figure 1b shows much less efficient gender classification of TIMBRE stimuli by CI users. Confirming this impression, significant differences were found between FULLcT and TIMBRE for ML80 and ML100, $|ts(27)| \geq 2.970$, $ps \leq .030$, and a trend for a difference between FULLcT and TIMBRE was also present for ML20 $|ts(27)| = 2.492$, $p = .057$ (uncorrected $p = .019$). TIMBRE was

significantly less effective in conveying gender information compared to F0 at ML0, ML80 and ML100, $|ts(27)| \geq 2.774$, $ps \leq .030$, although not at ML20, $|ts(27)| = 1.934$, $p = .191$ (uncorrected $p = .064$).

Performance group analysis.

The NH comprised a mean d_{gender} of .203 ($SD = .028$, range: .157 - .258). For the CI group d_{gender} was on average .393 ($SD = .089$, range: .249 - .537), with substantial differences between high ($M = .315$, $SD = .046$, range: .249 - .417) and low performing groups ($M = .471$, $SD = .036$, range: .421 - .537). Figure 2 shows individual data for each participant, ranked by d_{gender} , and illustrates that the best CI user (m202, a 12 year old male) had a classification pattern that was hardly discriminable from the NH patterns. Figure 3 shows data separately for the high and low performing groups. Due to performance close to chance, we decided to not formally analyze the low performing group.

-Please insert Figure 2 about here-

We directly compared high performers to NH listeners by a 3 x 2 x 6 x 2 ANOVA with factors MType, VCV, ML, and a between subject factor performance group (PerfGroup; NH vs. “high performers”). The results of this analysis (Table 4) were highly analogous to the ones obtained above including all CI users (Table 2). Of interest here is the three-way interaction PerfGroup x MType x ML (post hoc tests of the interaction involving VCV can be found in Supplemental Material Section 3.2.).

The interaction of PerfGroup x MType x ML indicates that the differences in the relative importance of the acoustic cues in CI users persist when the low performers were excluded from the analysis. As we were interested in differences in the relative importance of the morph types, we compared performance of the high performing CI directly with the NH listeners, separately for each morph type (Figure 3c) and ran three separate 6 x 2

ANOVAs (one per MType) with the factors ML and PerfGroup (cf. Table 4). In a second step, we calculated independent-sample separate variance t-tests (Welch) at each ML to compare the NH listeners with the high performing CI user group (cf. Table 5).

-Please insert Figure 3 about here-

For all three morph types, the ANOVA revealed a strong main effect of ML (Figure 3c, Table 4). While there was no main effect of PerfGroup, an interaction with ML was significant for the morph type FULLcT. Post hoc tests indicated that the high performing CI users gave significantly more female responses at ML0 and ML20 ($ps \leq .035$), and significantly less female responses (i.e. more male classifications) at ML80 ($p = .038$). Overall, this reflects poorer gender perception of FULLcT voice morphs in the high performing CI users compared to the NH. Intriguingly, for morph type F0 no clear group differences were found, indicating that F0 was similarly informative for both groups.

In striking contrast, for morph type TIMBRE the interaction of PerfGroup x ML revealed substantial group differences which corroborate poor ability to use timbre cues even in high performing CI users, who showed a less clear gender categorization at morph levels 20, 40, 80 and 100 ($ps \leq .001$), relative to NH listeners.

Interim summary.

NH listeners used F0 and timbre to a similar extent for gender classifications, and each cue as a separate was less efficient when compared with a FULL morph condition. At the female end of morph continua, timbre information was somewhat more informative than F0. In contrast, F0 was much more important than timbre for CI users. Although individual differences in the CI user group were substantial, even high performing CI users predominantly used F0 as the cue to voice gender, with little evidence for efficient use of timbre, and virtually no difference in performance when comparing F0 and FULLcT condition. Remarkably, high performing CI users even tended to outperform NH

listeners in the F0 condition, a finding that might tentatively be attributed to the speculation that their performance was less affected by the androgynous timbre of voices in this condition.

Experiment 2 (Age)

Trials without a key press within the time window (errors of omission, $N = 84$) occurred in 1.24% of all experimental trials and were excluded from the analyses. No anticipatory responses were observed, but participants missed on average 1.8 trials ($SD = 1.8$, range: 0-7).

Initial analysis (all CI users).

An initial $2 \times 4 \times 2 \times 2 \times 2$ mixed ANOVA on the proportion of “>50” responses with the factors speaker sex (SpSex: female, male), morph type (MType: F0, FULL, TIMBRE, TIME), morph level (ML: 0, 100) and the between-subject factors LSex and LGroup, did not reveal a main effect or interactions involving LSex (all $ps \geq .109$). A subsequent ANOVA was therefore performed without factor LSex (cf. Table 6, for results). This analysis revealed the expected main effect of ML, with voices at ML 0 perceived as younger than voices at ML100 ($Ms = .346 \pm .020$, vs. $.644 \pm .020$, respectively). A main effect of SpSex indicates that male voices were perceived as older compared to female voices ($Ms = .586 \pm .026$, vs. $.404 \pm .027$, respectively).

However, several interactions involving LGroup qualified these main effects (cf. Table 6) and suggest substantial differences between NH participants and CI users. For instance, the interaction of LGroup x SpSex is driven by CI users, who classified the female voices as younger compared to the male voices ($Ms = .337 \pm .038$, vs. $.642 \pm .035$, respectively), whereas NH listeners gave virtually the same age classifications to female and male voices ($Ms = .502 \pm .023$, vs. $.503 \pm .027$, respectively). The two-way interaction of LGroup x ML simply reflected steeper classification functions, and thus better

performance overall, in NH participants compared with CI users. Two three-way interactions and a four-way interaction of LGroup x SpSex x MType x ML (Figures 4a, b) further qualified the differences between NH participants and CI users. We post hoc tested the 4-way interaction, by running 2 x 4 x 2 ANOVAs with factors SpSex, MType, and ML, separately for both listener groups.

-Please insert Figure 4 about here-

NH listeners.

For the NH group, the ANOVA revealed no main effect or interaction involving SpSex ($p > .07$), confirming comparable results for female and male speakers (Figure 4a). The main effect of ML confirmed that voices at ML100 were perceived as older compared to voices at ML0 ($M_s = .759 \pm .017$, and $.246 \pm .024$, respectively). However, the interaction of MType x ML indicates differential impact on age classifications of the different morph types. Comparing ML0 with ML100 separately per MType revealed that each of the four morph types transmitted perceivable age information, with voices at ML100 always perceived as older compared to voices at ML0, $|t_s(18)| \geq 2.590$, $p_s \leq .018$. Figure 4a suggests further that FULL morphs best discriminated between young and old speakers, followed by TIMBRE-, F0-, and TIME-morphs (cf. Table 7 for descriptive statistics). At ML0, all but one combinations of morph types differed significantly from each other, $|t_s(18)| \geq 3.005$, $p_s \leq .046$; the notable exception was F0 and TIME morphs, $|t_s(18)| = 1.535$, $p = .535$. For ML100 we found the analogous pattern, with no significant differences between F0 and TIME morph, $|t_s(18)| = 3.958$, $p_s = .055$, while all other pairings of morph types differed significantly, $|t_s(18)| \geq 3.577$, $p_s \leq .013$.

All CI users.

For the CI group (Figure 4b), an analogous analysis yielded a more complex pattern of results (Table 6). As for NH listeners, the analysis revealed the expected main

effect of ML and a qualifying interaction of MType x ML. Thus, on average CI users perceived voices at ML0 as younger compared to voices at ML100 ($M_s = .414 \pm .021$, and $.566 \pm .022$, respectively), and this effect was also modulated by MType. In striking contrast to the NH listeners, CI users further exhibited a prominent main effect of SpSex, indicating that female voices were perceived as younger compared to male voices ($M_s = .337 \pm .038$, and $.642 \pm .035$, respectively). This effect was further qualified by a two-way interaction of MType x ML and a three-way interaction of SpSex x MType x ML (Figure 4b; for separate formal post hoc tests to this interaction please see Supplemental Material, Section 4.1). Note that the performance group analysis below will be more informative to unpack in detail abilities and limitations of CI users in vocal age perception.

Performance group analysis.

The NH had a mean d_{age} of .316 ($SD = .050$, range: .269 - .480). In the CI group d_{age} was on average .448 ($SD = .057$, range: .333 - .533), and used to form a high ($M = .400$, $SD = .034$, range: .333 - .447) and low performing group ($M = .496$, $SD = .027$, range: .447 - .533). Supplemental Figures S5-S7 show individual age classification data for each participant, ranked by d_{age} . Figures 4c and 4d show the age classification results separately for the high and low performing groups, respectively.

Comparison of NH listeners and high performing CI users.

We compared the high performers to NH listeners by running a $4 \times 2 \times 2 \times 2$ ANOVA with factors MType, SpSex, ML, and a between subject factor performance group (PerfGroup: NH, “high performers”). These ANOVAs exhibited several interactions involving PerfGroup (Table 8) that are summarized below.

Importantly, compared to the analysis involving all 28 CI users, the effects of speaker sex were no longer significant ($p_s \geq .226$), with only one remaining trend in the four-way interaction of PerfGroup x MType x SpSex x ML ($p = .058$). A main effect of

MType reflected that F0 morphs were slightly more often classified as “>50” compared to TIME morphs, $|t(32)| = 3.724$, $p = .005$, while all other comparisons were nonsignificant in Bonferroni corrected pairwise t-Tests, $|ts(32)| \leq 2.1$, $ps \geq .2$ (with $Ms = .466 \pm .021$, $.502 \pm .013$, $.509 \pm .014$, $.526 \pm .015$, for TIME, FULL, TIMBRE, and F0, respectively).

As for the NH group analysis above, the interaction of MType x ML indicates steeper classification functions, and thus better performance for FULL, followed by TIMBRE, F0, and TIME morph type. Importantly, here, the general pattern of relative importance of the acoustical cues is qualitatively similar in the CI and the NH groups (though more pronounced in the NH group, as reflected in the interaction of PerfGroup x MType x ML, Supplemental Figures S8a). The interaction PerfGroup x ML simply reflected steeper classification functions, and thus better performance, in NH participants than CI users (Supplemental Figure S8b).

We post hoc tested the interaction of PerfGroup x MType x ML by directly comparing the groups separately for each morph type (Figure 5) in four separate 2 x 2 ANOVAs with factors PerfGroup and ML (cf. Table 8 for details on all ANOVAs). All four ANOVAs yielded the expected main effect of ML, indicating that all cues contribute to age perception. Importantly, the interaction of PerfGroup x ML was significant for both FULL and TIMBRE morphs (with steeper slopes indicating better categorization for NH compared to high performing CI users), but not for F0 and TIME morphs ($ps \geq .217$), indicating that high performing CI users achieved similar age categorization than NH when based on TIME or F0 cues.

-Please insert Figure 5 about here-

Low performing CI users.

Figure 4d suggests that low performing CI users classified male voices (with low F0) as older than female voices (with higher F0). A 4 x 2 x 2 ANOVA with factors SpSex,

MType, and ML confirmed a substantial main effect of SpSex, $F(1,13) = 88.453$, $p < .001$, $\eta^2_p = .872$. Importantly, the lack of a main effect of ML, $F(1,13) = 0.073$, $p = .791$, $\eta^2_p = .006$, indicates that low performing CI users were very poor in discriminating young from old voices. Although the interaction MType x ML was significant, $F(3,39) = 4.622$, $p = .007$, $\eta^2_p = .262$, effect size was small compared to the main effect of SpSex, and performance was poor for each morph type (Supplemental Figure S9a). The interaction of SpSex x ML, $F(3,39) = 4.622$, $p = .007$, $\eta^2_p = .040$ (Supplemental Figure S9b) strengthens our conclusion that low performing CI users judged age based on F0, since sexual dimorphism in F0 was less pronounced in old speakers (Supplemental Figure S19).

Interim summary.

Taken together, all three morph types F0, TIMBRE, and TIME carry relevant, perceivable age information. Temporal information in TIME morphs revealed least information about age, followed closely by F0. TIMBRE clearly was the most important cue for age classification in NH listeners, although performance was best for the FULL morph condition. High performing CI users exhibited a similar pattern with best performance for FULL morphs, followed by TIMBRE, F0 and TIME. While NH outperformed high performing CI users for both FULL and TIMBRE morphs, no corresponding difference was significant for F0 and TIME morphs. Low performing CI users were generally unable to judge vocal age above chance levels; instead, they used F0 as a misleading cue to vocal age, classifying female voices as young and male voices as old.

Correlational Analyses

In the CI group, performance in gender perception was higher compared to performance in age perception, at least when comparing d_{gender} with d_{age} , $t(27) = -4.001$, $p < .001$ ($M = .393$, $SD = .090$, $M = .448$, $SD = .057$, respectively). Both scores were

correlated, $r = .592$, $p < .001$, $N = 28$, Pearson, two-tailed, cf. Figure 6.

-Please insert Figure 6 about here-

To evaluate whether performance scores were associated with overall CI satisfaction and user specific variables (such as age or duration of deafness), we calculated Persons correlations (two-tailed) and summarize the main findings below (see Supplemental Material Section 5, Table S8 and Figure S11 for details).

Seven CI users reported to be “fully satisfied (3)” with the CI in everyday life situations, 16 were “satisfied (2)”, 5 were “less satisfied (1)”, and no participant was “not satisfied (0)”. To analyze relationships with performance scores, we calculated an ANOVA for both d_{gender} and d_{age} , with “CI satisfaction group” as a between-subject factor, followed by Wilcoxon rank sum tests for unequal sample sizes with variable variance. This revealed no effect of group on d_{gender} , $F(2,25) = 1.010$, $p = .378$, but a main effect of group for d_{age} , $F(2,25) = 7.199$, $p = .003$, $\eta_p^2 = .365$, with significant differences between satisfaction levels 1 and 3, and between levels 2 and 3, but not between 1 and 2 (cf. Table 9 for descriptive statistics). Note that power of this ANOVA suffers from small group sizes. However, additional correlation analyses revealed that CI satisfaction also was highly correlated with overall performance (coded as $-I*d$, to account for the fact that lower difference scores reflect better performance) in the age experiment, $-d_{age}$, $r = .604$, $p = .001$, and moderately correlated with performance on TIMBRE morphs in the gender experiment, $-d_{genderTIMBRE}$, $r = .433$, $p = .021$.

We also found some evidence to indicate that performance in voice gender perception (but not vocal age perception) decreased with chronological age and with age at first implantation. In turn, performance in vocal age perception tended to decrease with the duration of deafness, and to increase with years of CI experience. Note that because these variables are not independent in our sample (e.g., our older participants tended to

have substantially less CI experience), caution is indicated when interpreting these findings (cf. Supplemental Material Section 5 for details).

Discussion

Using a parameter-specific voice morphing approach, we here investigated CI users' ability to use acoustical cues for voice gender and, for the first time, vocal age perception.

Gender Perception

For NH listeners, our results confirm earlier reports of a substantial impact of both timbre and F0 for voice gender perception (Pernet, Belin, & Jones, 2014; Skuk et al., 2015; Skuk & Schweinberger, 2014), though with a slightly greater role of timbre compared to F0 at the female end of the morph continuum.

Confirming earlier reports, CI users exhibited limitations in gender perception, used mainly F0 for the task (Fuller et al., 2014; Gaudrain & Baskent, 2018; Meister et al., 2016), but also showed substantial individual differences in overall performance (Fuller et al., 2014; Kovacic & Balaban, 2009; Massida et al., 2013; Wilkinson, Abdel-Hamid, Galvin, Jiang, & Fu, 2013). Previous CI studies reported that VTL contributes to gender perception significantly less than F0 (Fuller et al., 2014; Gaudrain & Baskent, 2018; Meister et al., 2016). Our present data show an intriguingly clear pattern, in that CI users almost exclusively relied on F0 but were largely unable to utilize timbre cues for vocal gender perception (cf. Figures 1 and 3).

We observed prominent individual differences in CI users, and captured these by a performance measure d that quantifies deviation from NH performance, similar to the approach by Fuller et al. (2014). Splitting CI users into high and low performers revealed that voice gender perception was at or close to chance in low performing CI users. Voice gender perception by high performing CI users, although at levels that approached NH

performance in individual cases, again was strongly reliant on F0, with little evidence for successful use of timbre cues. Intriguingly, when only F0 cues were available, high-performing CI users tended to outperform NH listeners. This is reminiscent of findings by Meister et al. (2009), and may perhaps reflect that CI users were less influenced by (ambiguous) timbre cues in this particular condition. Note that in voices with an ambiguous F0, high performing CI users showed very limited ability to utilize timbre in this task.

While Meister et al. (2009) reported a bias towards “male” ratings especially in ambiguous stimuli, we did not observe a similar bias. Meister et al. (2009) referred to a general “male” bias as reported by Mullennix, Pisoni, and Martin (1989), whereas we suggest that contrastive voice adaptation (Schweinberger et al., 2008) could also have influenced their results. This is because their stimulus set incorporated more female voice features, since both in their F0 and their VTL-conditions the constant cue (either VTL or F0) remained female, while only the cue of interest was shifted towards male. Compared to their approach, the present parameter-specific morphing approach a) avoids such biases by keeping constant features at a gender-neutral intermediate level, and b) generates naturally sounding voice tokens, without combining gender cues at different parameters that are in opposition to each other.

Age Perception

Experiment 2 represents the first study to investigate the relative importance of F0, timbre and temporal cues for vocal age perception. Across speaker sex, NH listeners predominately used timbre information, with decreasing contributions by F0 and time cues for age perception. Thus, rather than focusing on single cues, NH listeners appear to use a range of acoustical changes that also affect male and female voices during aging (Linville, 1996).

It is remarkable that, qualitatively, CI users showed a similar pattern of relative importance of acoustic cues for vocal age perception than NH listeners did. This not only is in striking contrast to the findings from Experiment 1, it also shows that CI users were not generally unable to process timbre cues. Rather, their ability to utilize acoustic parameters appears to depend on the specific social signal that defines the perceptual task. This finding also suggests a degree of flexibility and context dependency in cue usage, perhaps indicating that the development of perceptual training programmes for prioritized aspects of nonverbal voice perception might be promising.

As for voice gender perception, we again observed substantial individual differences in vocal age perception in CI users, and found that these accounted for some seemingly paradoxical findings in the CI group as a whole. In particular, while low performing CI users were at chance levels in vocal age perception overall, they showed a striking pattern of mistakenly using F0 as a cue to vocal age, and thus classified female voices as young and male voices as old. A possibility is that this finding relates to the fact that female F0 is much closer to childrens' typical F0 (~275 Hz, Kreiman and Sidtis, 2019). High performing CI users did not show this mistaken use of F0 at all. As a group, they were still outperformed by NH listeners in perceiving timbre cues to age – direct comparisons between NH and high performing CI users revealed a significant impairment of the latter to use timbre cues, but no significant impairments to use F0 and time cues for vocal age perception. Although this finding should be seen in the context of the task and the fact that even NH listeners made only moderate use of F0 and temporal cues for age perception, both Experiments 1 and 2 therefore revealed substantial impairments of CI users to perceive timbre, in the context of relatively preserved processing of F0. When looking at individual data (Supplemental Fig. S5), it is worth noting that a few high performing CI users appeared to efficiently use timbre, F0, and timing information within

the normal range of NH listeners during vocal age perception.

Fuller et al. (2014) proposed two hypotheses to explain poor timbre perception in gender perception: First, CI users may be unable to perceive timbre information because the wide spread excitation of electrical stimulation prevents timbre to be represented in the neural activation pattern. A second alternative is that timbre information “...*remains available to some extent in the neural representation but is either too weak or too distorted to be reliably used...*” (p. 1046). Our results from Experiment 2 are more in line with the second hypothesis: A substantial number of high performing CI users could use timbre information in vocal age perception, demonstrating that timbre cues can be neurally represented by CI users. In that sense, the results of Experiment 2 provide promising and novel insights into the perception of timbre as mediated via cochlear implants.

Factors associated with performance

Our findings of substantial individual differences in CI users’ abilities to perceive nonverbal social signals in voices is consistent with other reports of high variability in CI users performance (Blamey et al., 2013; Fuller et al., 2014; Kovacic & Balaban, 2009). It is therefore important to identify factors that can be systematically associated with CI users' performance in the perception of nonverbal information in voices.

A first remarkable observation is that CI users’ performance in tasks to perceive vocal gender and vocal age in both Experiments was highly ($r = .592$) correlated (Figure 6). This could be partly due to the heterogeneous sample tested, with other variables (such as, for instance, age or individual hearing history) exerting a common effect on both tasks. Despite this finding, there is still a lack of research towards revealing profiles of abilities of CI users to perceive different nonverbal signals (e.g., gender, age, identity recognition, identity matching, affect recognition) in voices. At a case level, it may be noted that a few of the present CI users with very poor abilities to process vocal gender (e.g., m209, f112)

were relatively high performing in vocal age perception, whereas other CI users with poor vocal age perception (e.g. m801, f103) performed remarkably well in gender perception (cf. Figures 2 and S5). These informal observations indicate that it could be important to study several different aspects of voice perception in the same sample of CI users. When considering relevant findings on task dissociations in neuropsychological patients (Garrido et al., 2009; Neuner & Schweinberger, 2000; Van Lancker & Kreiman, 1987) and individuals with phonagnosia (Garrido et al., 2009), it will be an interesting challenge for future research to uncover whether systematic dissociations will also emerge when comparing individual CI users' performances in these tasks.

A second intriguing observation is the substantial ($r = .604$) correlation between experimental performance in vocal age perception and individual reports of satisfaction with the CI. This finding may be related to previous reports (Schorr et al., 2009) that abilities to perceive nonverbal social signals in voices can be highly relevant to experienced quality of life. While the majority of our CI users (82%, $N = 23$) was "satisfied" or "fully satisfied" with their CI in everyday life situation, individuals who were "less satisfied" exhibited lower performance scores in the age experiment, compared to "fully satisfied" CI users. This not only suggests the importance of vocal age perception for social communication in general (Montepare & Zebrowitz, 1998), it also complements findings by Schorr et al. (2009) on vocal emotion perception, showing that perceived quality of life was correlated with identification of non-linguistic emotional sounds, but not with word recognition as assessed by the Lexical Neighborhood Test (Kirk et al., 1995). Overall, future research is therefore warranted to more systematically investigate the role of nonverbal voice perception abilities for CI satisfaction and quality of life in CI users.

We found that both younger CI users and CI users who were first implanted at a

younger age performed better in voice gender perception. Analogous findings were less clear for vocal age perception, with the notable exception of a correlation between “chronological age” and $d_{\text{age}TIME}$, reflecting that younger CI users made better usage of temporal information in the sentence stimuli. Across both experiments, and particularly for voice gender perception, we also found that a younger age at first CI implantation was associated with better performance, confirming earlier findings by Kovacic and Balaban (2009).

Blamey et al. (2013) reported that both duration of deafness and duration of CI experience in post-lingually deafened CI users were related with performance in speech perception tasks. Similarly, we also found that shorter duration of deafness and longer experience with the CI were associated with better performance in nonverbal voice perception tasks, particularly when considering timbre perception (Supplemental Table 9). These findings may reflect effects of auditory deprivation and functional changes related to post-implant cortical plasticity. However, we should note that these findings need to be interpreted with caution, because our younger participants also had longer CI experience. Accordingly, it remains somewhat unclear whether performance in older CI users was lower as a result of age per se, or as a result of lower levels of CI experience, and more research is needed to disentangle the effects of these two factors.

Limitations

One limitation of our experimental design was that the gender experiment was always conducted before the age experiment. We decided to fix the order of experiments both in the interest of studying interindividual differences and for practical considerations, because we were unsure whether all CI users would be able to complete both experiments, especially when the more challenging age experiment would be conducted first. As a consequence though, we cannot entirely rule out systematic effects of task order. For

instance, it remains possible that CI users' focus on F0 for voice gender perception might have primed their perceptual strategy for the vocal age perception task. However, we think that the actual findings from the age task (in which high performing CI users did use timbre cues rather than focusing on F0) suggest that order effects were not a dominant factor to explain the present results.

Albeit all NH listeners reported no hearing problems, their hearing status was not confirmed by an audiologist. In retrospect, we cannot be entirely sure whether response pattern of individual NH listeners occasionally could reflect a degree of hearing loss. For instance, one 85-year old man seemed to be unable to perceive vocal age (Supplemental Figure S5, code m406), although preserved voice gender perception (Figure 2) does not suggest that any hearing loss generally prevented voice perception. The present decision to include all NH participants in the data analysis also reflected our aim for NH listeners to cover the entire age range of CI users tested.

It should be acknowledged that different hearing histories of CI users may have contributed to the substantial individual differences in performance we observed. Variability between CI users should be seen as the rule rather than the exception (Blamey et al., 2013; Fuller et al., 2014; Kovacic & Balaban, 2010; Li & Fu, 2011), such that it seems important to develop procedures and methods to assess individual voice perception abilities, independent of speech recognition scores. The present approach to capture individual CI user's abilities in voice perception could be developed into a valuable source of information for researchers, but also for clinical audiologist to capture communicative aspects of hearing beyond established speech recognition scores.

Perspectives

Regarding the potential of parameter-specific voice morphing for application, we would like to note that this technology also allows creating more salient versions

(caricatures) of social signals, such as age, gender, emotionality, speaker identity, or other target signals. In the visual domain, it has been demonstrated that facial caricaturing can enhance face perception across a range of conditions (Dawel et al., 2019; Itz, Schweinberger, Schulz, & Kaufmann, 2014), for instance in individuals with sensory impairments such as age-related macular degeneration (Lane et al., 2018), or individuals with poor face recognition skills (Kaufmann, Schulz, & Schweinberger, 2013). Although the role of stimulus enhancement/caricaturing for nonverbal social perception is better established in the visual domain for faces, compared to voices, other seminal findings showed that training with acoustically enhanced discriminative phonetic features can improve language comprehension in language-learning impaired children (Tallal et al., 1996). Such findings indicate that it could be promising to explore the potential of voice caricaturing, both for perceptual training and towards enhanced CI technology, with the goal to improve nonverbal auditory communications in specific target groups.

Conclusions

The present study confirms and extends earlier findings regarding the role of acoustic cues for voice gender perception in CI users, using a novel parameter-specific voice morphing approach. In line with earlier research, our data confirm and refine a dominance of F0 in voice gender perception, with little evidence for the usage of timbre cues. Importantly, our new results on vocal age perception demonstrate that a substantial number of CI users can utilize timbre information in principle, suggesting that timbre processing depends on the social signal being processed. Of practical relevance, CI satisfaction was associated with performance in voice perception, and vocal age in particular, and appeared related to the ability to perceive timbre. The extent and nature of individual differences in voice perception abilities further suggest that a simultaneous study of different aspects of voice perception in CI users is promising. Overall, we

propose that the present parameter-specific voice morphing approach is a promising new tool to investigate the relative contribution of different acoustical cues to the perception of different types of nonverbal information (e.g., gender, age, identity, affect, intonation) in voices, both in NH listeners and CI users. From a rehabilitation perspective, such an approach could promote (1) individual tailor-made training programs to improve voice perception abilities, and (2) optimizing coding strategies of CIs whenever a focus on particular social cues (e.g., identity, gender, age, emotion) is desirable.

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References

- Agrawal, D., Thorne, J. D., Viola, F. C., Timm, L., Debener, S., Buchner, A., . . . Wittfoth, M. (2013). Electrophysiological responses to emotional prosody perception in cochlear implant users. *Neuroimage-Clinical*, 2, 229-238. doi:10.1016/j.nicl.2013.01.001
- Assmann, P. F., Dembling, S., & Nearey, T. M. (2006). *Effects of frequency shifts on perceived naturalness and gender information in speech*. Paper presented at the Interspeech 2006, ICSLP, Pittsburg, PA.
- Blamey, P., Artieres, F., Baskent, D., Bergeron, F., Beynon, A., Burke, E., . . . Lazard, D. S. (2013). Factors affecting auditory performance of postlinguistically deaf adults using cochlear implants: an update with 2251 patients. *Audiol Neurotol*, 18(1), 36-47. doi:10.1159/000343189
- Boersma, P., & Weenink, D. (2011). Praat: Doing Phonetics by Computer. *Ear and Hearing*, 32(2), 266. doi:10.1097/AUD.0b013e31821473f7
- Caldwell, M. T., Jiam, N. T., & Limb, C. J. (2017). Assessment and Improvement of Sound Quality in Cochlear Implant Users. *Laryngoscope Investigative Otolaryngology*, 2(3), 119-124. doi:10.1002/lio2.71

- Carroll, J., & Zeng, F.-G. (2007). Fundamental frequency discrimination and speech perception in noise in cochlear implant simulations. *Hearing Research*, 231(1-2), 42-53. doi:10.1016/j.heares.2007.05.004
- Dawel, A., Wong, T. Y., McMorrow, J., Ivanovici, C., He, X. M., Barnes, N., . . . McKone, E. (2019). Caricaturing as a General Method to Improve Poor Face Recognition: Evidence From Low-Resolution Images, Other-Race Faces, and Older Adults. *Journal of Experimental Psychology-Applied*, 25(2), 256-279. doi:10.1037/xap0000180
- Fu, Q. J., Chinchilla, S., & Galvin, J. J. (2004). The role of spectral and temporal cues in voice gender discrimination by normal-hearing listeners and cochlear implant users. *Jaro-Journal of the Association for Research in Otolaryngology*, 5(3), 253-260. doi:DOI 10.1007/s10162-004-4046-1
- Fu, Q. J., Chinchilla, S., Nogaki, G., & Galvin, J. J. (2005). Voice gender identification by cochlear implant users: The role of spectral and temporal resolution. *Journal of the Acoustical Society of America*, 118(3), 1711-1718. doi:10.1121/1.1985024
- Fuller, C. D., Gaudrain, E., Clarke, J. N., Galvin, J. J., Fu, Q.-J., Free, R. H., & Baskent, D. (2014). Gender categorization is abnormal in cochlear implant users. *Journal of the Association for Research in Otolaryngology : JARO*, 15(6), 1037-1048. doi:10.1007/s10162-014-0483-7
- Garrido, L., Eisner, F., McGettigan, C., Stewart, L., Sauter, D., Hanley, J. R., . . . Duchaine, B. (2009). Developmental phonagnosia: A selective deficit of vocal identity recognition. *Neuropsychologia*, 47(1), 123-131. doi:10.1016/j.neuropsychologia.2008.08.003
- Gaudrain, E., & Baskent, D. (2018). Discrimination of Voice Pitch and Vocal-Tract Length in Cochlear Implant Users. *Ear and Hearing*, 39(2), 226-237. doi:10.1097/aud.0000000000000480
- Gonzalez, J., & Oliver, J. C. (2005). Gender and speaker identification as a function of the number of channels in spectrally reduced speech. *Journal of the Acoustical Society of America*, 118(1), 461-470. doi:10.1121/1.1928892
- Hazrati, O., Ali, H., Hansen, J. H. L., & Tobey, E. (2015). Evaluation and analysis of whispered speech for cochlear implant users: Gender identification and intelligibility. *Journal of the Acoustical Society of America*, 138(1), 74-79. doi:10.1121/1.4922230
- Henton, C. G., & Bladon, R. A. W. (1985). Breathiness in Normal Female Speech - Inefficiency Versus Desirability. *Language and Communication*, 5(3), 221-227. doi:10.1016/0271-5309(85)90012-6
- Hillenbrand, J., & Clark, M. J. (2009). The role of f0 and formant frequencies in distinguishing the voices of men and women. *Attention Perception and Psychophysics*, 71(5), 1150-1166. doi:10.3758/app.71.5.1150
- Itz, M. L., Schweinberger, S. R., Schulz, C., & Kaufmann, J. M. (2014). Neural correlates of facilitations in face learning by selective caricaturing of facial shape or reflectance. *Neuroimage*, 102 Pt 2, 736-747. doi:10.1016/j.neuroimage.2014.08.042
- Jiam, N. T., Caldwell, M., Deroche, M. L., Chatterjee, M., & Limb, C. J. (2017). Voice emotion perception and production in cochlear implant users. *Hearing Research*, 352, 30-39. doi:10.1016/j.heares.2017.01.006
- Kaufmann, J. M., Schulz, C., & Schweinberger, S. R. (2013). High and low performers differ in the use of shape information for face recognition. *Neuropsychologia*, 51(7), 1310-1319. doi:10.1016/j.neuropsychologia.2013.03.015
- Kawahara, H., Estill, J., & Fujimura, O. (2001). Aperiodicity extraction and control using

- 927 mixed mode excitation and group delay manipulation for a high quality speech
 928 analysis, modification and synthesis system STRAIGHT. *Proc. 2nd MAVEBA*, 13-
 929 -15.
- 930 Kawahara, H., Katayose, H., de Cheveigné, A., & Patterson, R. D. (1999). *Fixed point*
 931 *analysis of frequency to instantaneous frequency mapping for accurate estimation*
 932 *of F0 and periodicity*. Paper presented at the Proc. Eurospeech.
- 933 Kawahara, H., Masuda-Katsuse, I., & de Cheveigne, A. (1999). Restructuring speech
 934 representations using a pitch-adaptive time-frequency smoothing and an
 935 instantaneous-frequency-based F0 extraction: Possible role of a repetitive structure
 936 in sounds. *Speech Communication*, 27(3-4), 187-207. doi:10.1016/S0167-
 937 6393(98)00085-5
- 938 Kawahara, H., Morise, M., Banno, H., & Skuk, V. G. (2013). *Temporally variable multi-*
 939 *aspect N-way morphing based on interference-free speech representations*. Paper
 940 presented at the Signal and Information Processing Association Annual Summit
 941 and Conference (APSIPA), 2013 Asia-Pacific.
- 942 Kawahara, H., Morise, M., Takahashi, T., Nisimura, R., Irino, T., & Banno, H. (2008).
 943 *TANDEM-STRAIGHT: A temporally stable power spectral representation for*
 944 *periodic signals and applications to interference-free spectrum, F0, and*
 945 *aperiodicity estimation*. Paper presented at the IEEE 2008 ICASSP, Las Vegas,
 946 Nevada, U.S.A.
- 947 Kawahara, H., & Skuk, V. G. (2018). Voice Morphing. . In S. Frühholz & P. Belin (Eds.),
 948 *The Oxford Handbook of Voice Perception*. Oxford: Oxford University Press.
- 949 Kim, M. Y., & Yoon, M. S. (2018). Recognition of Voice Emotion in School Aged
 950 Children with Cochlear Implants. *Communication Sciences and Disorders-Csd*,
 951 23(4), 1102-1110. doi:10.12963/csd.18569
- 952 Kirk, K. I., Pisoni, D. B., & Osberger, M. J. (1995). Lexical Effects on Spoken Word
 953 Recognition by Pediatric Cochlear Implant Users. *Ear and Hearing*, 16(5), 470-
 954 481. doi:10.1097/00003446-199510000-00004
- 955 Kovacic, D., & Balaban, E. (2009). Voice gender perception by cochlear implantees.
 956 *Journal of the Acoustical Society of America*, 126(2), 762-775.
 957 doi:10.1121/1.3158855
- 958 Kovacic, D., & Balaban, E. (2010). Hearing history influences voice gender perceptual
 959 performance in cochlear implant users. *Ear Hear*, 31(6), 806-814.
 960 doi:10.1097/AUD.0b013e3181ee6b64
- 961 Kreiman, J., & Sidtis, D. (2011). Physical characterisitics and the Voice: Can we Hear
 962 What a Speaker Looks Like? *Foundations of Voice Studies: An Interdisciplinary*
 963 *Approach to Voice Production and Perception* (pp. 110-155). Chichester, West
 964 Sussex, UK: Wiley-Blackwell.
- 965 Lane, J., Rohan, E. M. F., Sabeti, F., Essex, R. W., Maddess, T., Barnes, N., . . . McKone,
 966 E. (2018). Improving face identity perception in age-related macular degeneration
 967 via caricaturing. *Sci Rep*, 8(1), 15205. doi:10.1038/s41598-018-33543-3
- 968 Li, T. H., & Fu, Q. J. (2011). Voice gender discrimination provides a measure of more
 969 than pitch-related perception in cochlear implant users. *International Journal of*
 970 *Audiology*, 50(8), 498-502. doi:10.3109/14992027.2011.576274
- 971 Linville, S. E. (1996). The sound of senescence. *Journal of Voice*, 10(2), 190-200.
 972 doi:10.1016/S0892-1997(96)80046-4
- 973 Linville, S. E., & Rens, J. (2001). Vocal tract resonance analysis of aging voice using
 974 long-term average spectra. *Journal of Voice*, 15(3), 323-330. doi:10.1016/S0892-
 975 1997(01)00034-0
- 976 Massida, Z., Marx, M., Belin, P., James, C., Fraysse, B., Barone, P., & Deguine, O.

- 977 (2013). Gender Categorization in Cochlear Implant Users. *Journal of Speech*
 978 *Language and Hearing Research*, 56(5), 1389-1401. doi:10.1044/1092-
 979 4388(2013/12-0132)
- 980 Meister, H., Fursen, K., Streicher, B., Lang-Roth, R., & Walger, M. (2016). The Use of
 981 Voice Cues for Speaker Gender Recognition in Cochlear Implant Recipients.
 982 *Journal of Speech Language and Hearing Research*, 59(3), 546-556.
 983 doi:10.1044/2015_jslhr-h-15-0128
- 984 Meister, H., Landwehr, M., Pyschny, V., Walger, M., & von Wedel, H. (2009). The
 985 perception of prosody and speaker gender in normal-hearing listeners and cochlear
 986 implant recipients. *International Journal of Audiology*, 48(1), 38-48.
 987 doi:10.1080/14992020802293539
- 988 Montepare, J. M., & Zebrowitz, L. A. (1998). Person Perception Comes of Age: The
 989 Salience and Significance of Age in Social Judgments. In M. P. Zanna (Ed.),
 990 *Advances in Experimental Social Psychology* (Vol. 30, pp. 93-161): Academic
 991 Press.
- 992 Morris, R. J., & Brown, W. S. (1994). Age-Related Differences in Speech Intensity among
 993 Adult Females. *Folia Phoniatrica Et Logopaedica*, 46(2), 64-69. doi:Doi
 994 10.1159/000266294
- 995 Muhler, R., Ziese, M., & Verhey, J. L. (2017). Speaker discrimination in cochlear implant
 996 users. *HNO*, 65(3), 243-249. doi:10.1007/s00106-016-0225-8
- 997 Mullennix, J. W., Pisoni, D. B., & Martin, C. S. (1989). Some Effects of Talker
 998 Variability on Spoken Word Recognition. *Journal of the Acoustical Society of*
 999 *America*, 85(1), 365-378. doi:Doi 10.1121/1.397688
- 1000 Neuner, F., & Schweinberger, S. R. (2000). Neuropsychological impairments in the
 1001 recognition of faces, voices, and personal names. *Brain and Cognition*, 44(3), 342-
 1002 366. doi:10.1006/brcg.1999.1196
- 1003 Paquette, S., Ahmed, G. D., Goffi-Gomez, M. V., Hoshino, A. C. H., Peretz, I., &
 1004 Lehmann, A. (2018). Musical and vocal emotion perception for cochlear implants
 1005 users. *Hearing Research*, 370, 272-282. doi:10.1016/j.heares.2018.08.009
- 1006 Pernet, C. R., & Belin, P. (2012). The role of pitch and timbre in voice gender
 1007 categorization. *Frontiers in Psychology*, 3, 1-11. doi:10.3389/fpsyg.2012.00023
- 1008 Pernet, C. R., Belin, P., & Jones, A. (2014). Behavioral evidence of a dissociation between
 1009 voice gender categorization and phoneme categorization using auditory morphed
 1010 stimuli. *Frontiers in Psychology*, 4. doi:10.3389/fpsyg.2013.01018
- 1011 Peterson, N. R., Pisoni, D. B., & Miyamoto, R. T. (2010). Cochlear implants and spoken
 1012 language processing abilities: Review and assessment of the literature. *Restor*
 1013 *Neurol Neurosci*, 28(2), 237-250. doi:10.3233/Rnn-2010-0535
- 1014 Pijl, S., & Schwarz, D. W. (1995). Melody recognition and musical interval perception by
 1015 deaf subjects stimulated with electrical pulse trains through single cochlear implant
 1016 electrodes. *Journal of the Acoustical Society of America*, 98(2 Pt 1), 886-895.
- 1017 Pisoni, D. B., Cleary, M., Geers, A. E., & Tobey, E. A. (1999). Individual Differences in
 1018 Effectiveness of Cochlear Implants in Children Who Are Prelingually Deaf: New
 1019 Process Measures of Performance. *The Volta review*, 101(3), 111-164.
- 1020 Reubold, U., Harrington, J., & Kleber, F. (2010). Vocal aging effects on F0 and the first
 1021 formant: A longitudinal analysis in adult speakers. *Speech Communication*, 52(7-
 1022 8), 638-651. doi:10.1016/j.specom.2010.02.012
- 1023 Ryan, W. J. (1972). Acoustic Aspects of the Aging Voice. *Journals of Gerontology*, 27(2),
 1024 265-&. doi:10.1093/geronj/27.2.265
- 1025 Schneider, W., Eschman, A., & Zuccolotto, A. (2002). E-Prime User's Guide. Pittsburgh:
 1026 Psychology Software Tools Inc. .

- Schorr, E. A., Roth, F. P., & Fox, N. A. (2009). Quality of Life for Children With Cochlear Implants: Perceived Benefits and Problems and the Perception of Single Words and Emotional Sounds. *Journal of Speech Language and Hearing Research*, 52(1), 141-152. doi:10.1044/1092-4388(2008/07-0213)
- Schweinberger, S. R., Casper, C., Hauthal, N., Kaufmann, J. M., Kawahara, H., Kloth, N., . . . Zäske, R. (2008). Auditory adaptation in voice perception. *Current Biology*, 18(9), 684-688. doi:10.1016/j.cub.2008.04.015
- Schweinberger, S. R., Kawahara, H., Simpson, A. P., Zäske, R., & Skuk, V. G. (2014). Speaker Perception. *Wiley Interdisciplinary Reviews: Cognitive Science*. doi:10.1002/wcs.1261
- Schweinberger, S. R., Walther, C., Zäske, R., & Kovacs, G. (2011). Neural correlates of adaptation to voice identity. *British Journal of Psychology*, 102, 748-764. doi:10.1111/j.2044-8295.2011.02048.x
- Simpson, A. P. (2009). Phonetic differences between male and female speech. *Language and Linguistics Compass*, 3(2), 621-640. doi:10.1111/j.1749-818X.2009.00125.x
- Skuk, V. G., Dammann, L. M., & Schweinberger, S. R. (2015). Role of timbre and fundamental frequency in voice gender adaptation. *Journal of the Acoustical Society of America*, 138(2), 1180-1193. doi:10.1121/1.4927696
- Skuk, V. G., & Schweinberger, S. R. (2014). Influences of Fundamental Frequency, Formant Frequencies, Aperiodicity, and Spectrum Level on the Perception of Voice Gender. *Journal of Speech Language and Hearing Research*, 57(1), 285-296. doi:10.1044/1092-4388(2013/12-0314)
- Smith, D. R. R., & Patterson, R. D. (2005). The interaction of glottal-pulse rate and vocal-tract length in judgements of speaker size, sex, and age. *Journal of the Acoustical Society of America*, 118(5), 3177-3186. doi:10.1121/1.2047107
- Smith, E. L., Grabowecy, M., & Suzuki, S. (2007). Auditory-visual crossmodal integration in perception of face gender. *Current Biology*, 17(19), 1680-1685. doi:10.1016/j.cub.2007.08.043
- Tallal, P., Miller, S. L., Bedi, G., Byma, G., Wang, X. Q., Nagarajan, S. S., . . . Merzenich, M. M. (1996). Language comprehension in language-learning impaired children improved with acoustically modified speech. *Science*, 271(5245), 81-84. doi:10.1126/science.271.5245.81
- Thomas, M., & Tripathi, S. (2014). Music Perception and Cochlear Implants-A Review of major breakthroughs. In N. Krishnan & M. Karthikeyan (Eds.), *2014 Ieee International Conference on Computational Intelligence and Computing Research* (pp. 788-795).
- Tinnemore, A. R., Zion, D. J., Kulkarni, A. M., & Chatterjee, M. (2018). Children's Recognition of Emotional Prosody in Spectrally Degraded Speech Is Predicted by Their Age and Cognitive Status. *Ear and Hearing*, 39(5), 874-880. doi:10.1097/aud.0000000000000546
- Van Lancker, D., & Kreiman, J. (1987). Voice Discrimination and Recognition Are Separate Abilities. *Neuropsychologia*, 25(5), 829-834. doi:10.1016/0028-3932(87)90120-5
- Vongphoe, M., & Zeng, F. G. (2005). Speaker recognition with temporal cues in acoustic and electric hearing. *Journal of the Acoustical Society of America*, 118(2), 1055-1061. doi:10.1121/1.1944507
- Waaramaa, T., Kukkonen, T., Mykkanen, S., & Geneid, A. (2018). Vocal Emotion Identification by Children Using Cochlear Implants, Relations to Voice Quality, and Musical Interests. *Journal of Speech Language and Hearing Research*, 61(4), 973-985. doi:10.1044/2017_jslhr-h-17-0054

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- 1077 Wilkinson, E. P., Abdel-Hamid, O., Galvin, J. J., 3rd, Jiang, H., & Fu, Q. J. (2013). Voice
1078 conversion in cochlear implantation. *Laryngoscope*, 123 Suppl 3, S29-43.
1079 doi:10.1002/lary.23744
- 1080 Zäske, R., & Schweinberger, S. R. (2011). You are only as old as you sound: Auditory
1081 aftereffects in vocal age perception. *Hearing Research*, 282(1-2), 283-288.
1082 doi:10.1016/j.heares.2011.06.008
- 1083 Zäske, R., Skuk, V. G., Golle, J., & Schweinberger, S. R. (2019). The Jena Speaker Set
1084 (JESS)-A database of voice stimuli from unfamiliar young and old adult speakers.
1085 *Behavior Research Methods*. doi:10.3758/s13428-019-01296-0
- 1086 Zäske, R., Skuk, V. G., Kaufmann, J. M., & Schweinberger, S. R. (2013). Perceiving
1087 vocal age and gender: An adaptation approach. *Acta Psychologica*, 144(3), 583-
1088 593.

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Tables

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Table 1. Demographic and Technical Information regarding CI users ($N = 28$).

Gender/ Participant	Chron. Age (years)	Age at deafness (years)	Duration of deaf- ness (years)	Age at first CI (years)	Duration of CI experience (years)	Im- planted ear	Left ear CI			Right ear CI			Hearing aid
							Manu- facturer	Processor	Strategy	Manu- facturer	Processor	Strategy	
f101	35	0	31	31	4	bi	Cochlear	CP 810	ACE	Cochlear	CP 910	ACE	-
f102	85	60	24	84	<1	left	Cochlear	CP 910	ACE	-	-	-	Siemens Intuis
f103	62	0	58	58	3	left	Med-El	Opus-2	FS4	-	-	-	Siemens Centra S
f104	63	13	45	58	4	bi	Med-El	Opus-2	FS4	Med-El	Opus-2	FS4	-
f105	74	50	23	73	1	left	Med-El	Opus-2	FS4	-	-	-	Phonak Naida V
f107	46	0	38	38	7	bi	Med-El	Sonnet	FS4	Med-El	Opus-2	FS4	-
f108	70	50	12	62	8	bi	Med-El	Opus-2	FS4	Med-El	Sonnet	FS4	-
f109	74	67	5	72	2	right	-	-	-	Med-El	Opus-2	FS4	Phonak Audeo
f110	77	56	20	76	<1	left	Cochlear	CP 910	ACE	-	-	-	n.a.
f111	64	52	11	63	1	right	-	-	-	Cochlear	CP 910	ACE	Siemens Pure Carat
f112	78	66	6	72	6	bi	Med-El	Opus-2	FS4	Med-El	Opus-2	FS4	-
f113	41	19	13	32	9	bi	Med-El	Opus-2	FSP	Med-El	Sonnet	FS4	-
f114	61	7	52	59	2	right	-	-	-	Cochlear	CP 910	ACE	Audio Service BIZZ Duo
f115	74	40	30	70	4	bi	Med-El	Opus-2	FS4	Med-El	Opus-2	FS4	-
f116	60	55	2	57	2	bi	Med-El	Opus-2	FS4	Med-El	Opus-2	FS4	-
m201	62	61	0	61	1	right	-	-	-	Cochlear	CP 910	ACE	AS Astra Astral P
m202	12	0	4	4	8	bi	Cochlear	CP 910	ACE	Cochlear	C 810	ACE	-
m203	69	60	8	68	<1	right	-	-	-	Med-El	Opus-2	FS4	n.a.
m204	18	3	3	6	11	bi	Med-El	Opus-2	FSP	Med-El	Opus-2	HDCIS	-
m205	22	20	0	20	1	bi	Cochlear	CP 910	MP3000	Cochlear	CP 910	MP3000	-
m206	60	7	52	59	<1	left	Cochlear	CP 910	MP3000	-	-	-	Siemens Cielo S
m207	64	3	59	62	2	bi	Cochlear	CP 910	ACE	Cochlear	CP 910	ACE	-
m209	83	43	38	81	2	left	Med-El	Opus-2	FS4	-	-	-	H6 Kind 7ex
m210	70	25	42	67	2	bi	Med-El	Opus-2	FS4	Med-El	Opus-2	FS4	-

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m211	76	54	20	74	1	left	Med-El	Opus-2	FS4	-	-	-	Oticon Ergo P
m212	51	49	0	49	2	bi	Cochlear	CP 810	ACE	Cochlear	CP 910	ACE	-
m213	68	24	42	66	1	left	Cochlear	CP 910	ACE	-	-	-	-
m801	33	0	29	29	4	bi	Cochlear	CP 810	ACE	Cochlear	CP 810	ACE	-
M	59		23.8	55.4	3.1								
SD	19.7		19.2	21.5	3								
MIN	12		0	4	0								
MAX	85		59	84	11								
N	28		28	28	28								

Note. Participant gender is indicated by the letter preceding participant number: f = female, m = male; CI = Cochlear Implant; Chron. Age = chronological age; Age at deafness = age at which deafness occurred, 0 stands for prelingual hearing loss that was present at birth and before language acquisition; duration of CI = duration of CI experience since first implantation, bi = bilateral implant; left/right = unilateral left/right implant; ACE = advanced combination encoder; FSP = fine structure processing; FS4 = fine structure 4; HDCIS = high-definition continuous interleaved sampling; MP3000 = variation of ACE strategy, also known as psychoacoustic advanced combination encoder (PACE); n.a. = not available.

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Table 2. Gender Experiment. Results of the Initial ANOVA and Post hoc Analyses.

	<i>df1</i>	<i>df2</i>	<i>F</i>	<i>p</i>	ϵ_{HF}	η^2_p
Initial ANOVA on all listeners (19 NH and 28 CI users)						
ML	5	22	179.242	<.001	.481	.799
MType x ML	10	450	9.462	<.001	.541	.174
VCV x ML	5	225	5.240	<.001	.790	.104
LGroup x ML	5	225	30.846	<.001		.407
LGroup x MType	2	90	3.352	.039		.069
LGroup x MType x ML	10	450	8.728	<.001		.162
LGroup x VCV x ML	5	225	5.498	<.001		.109
Post hoc ANOVAs on ...						
... all NH listeners (N= 19)						
MType x ML						
MType	2	36	4.435	.019	.735	.198
ML	5	90	259.971	.000	.615	.935
MType x ML	10	180	12.929	.000	.867	.418
MType per ML:						
ML0	2	36	2.67	.083		.129
ML20	2	36	8.795	.001		.328
ML40	2	36	9.177	.001		.338
ML60	2	36	9.721	<.001		.351
ML80	2	36	14.238	<.001	.761	.442
ML100	2	36	14.882	<.001	.667	.453
... all CI users (N= 28)						
MType x ML						
MType	2	54	1.955	.151	.737	.068
ML	5	135	30.361	.000	.380	.529
MType x ML	10	270	9.712	.000	.380	.265
MType per ML:						
ML0	2	54	4.845	.012	.661	.152
ML20	2	54	4.845	.012	.661	.152
ML40	2	54	1.686	.195		.059
ML60	2	54	2.123	.130		.073
ML80	2	54	8.176	.001	.698	.232
ML100	2	54	23.864	<.001	.751	.469

Note. Top rows show significant main effects and interactions of the 3 x 2 x 6 x 2 ANOVA on the proportion of “female” responses with the factors Morph Type (MType: F0, FULLcT, TIMBRE), VCV (aba, igi), Morph Level (ML: 0, 20, 40, 60, 80, 100) and a between-subject factor Listener Group (LGroup: NH, CI). Lower rows show post hoc analyses separately per LGroup. Where indicated, the Huynh-Feldt Epsilon value ϵ_{HF} is given to adjust *p*-values.

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Table 3. Gender Experiment. Descriptive statistics for NH listeners ($N = 19$), cochlear implant users ($N = 28$), and for high and low performing CI users ($n = 14$, each).

MType	ML	Normal Hearing ($N = 19$)			CI user ($N = 28$)			High Performing CI users ($n = 14$)			Low Performing CI Users ($n = 14$)		
		<i>M</i>	<i>SE</i>	<i>CI</i>	<i>M</i>	<i>SE</i>	<i>CI</i>	<i>M</i>	<i>SE</i>	<i>CI</i>	<i>M</i>	<i>SE</i>	<i>CI</i>
FULLcT	0	.007	.007	.014	.299	.045	.092	.116	.038	.082	.482	.041	.089
	20	.022	.012	.025	.308	.047	.096	.143	.051	.109	.473	.049	.106
	40	.241	.049	.102	.430	.048	.098	.351	.060	.129	.509	.070	.151
	50*	.592	.056	.117	.496	.048	.098	.515	.060	.131	.476	.076	.163
	60	.842	.047	.098	.597	.041	.084	.708	.051	.111	.485	.048	.104
	80	.987	.009	.019	.765	.046	.095	.923	.027	.057	.607	.067	.144
	100	.993	.007	.014	.804	.053	.109	.946	.025	.055	.661	.089	.193
F0	0	.046	.022	.046	.260	.040	.082	.071	.025	.055	.449	.024	.051
	20	.151	.042	.088	.326	.038	.078	.161	.036	.077	.491	.024	.053
	40	.382	.048	.101	.405	.043	.087	.348	.069	.149	.461	.048	.104
	60	.664	.054	.114	.595	.042	.085	.688	.061	.131	.503	.047	.101
	80	.776	.047	.100	.754	.051	.105	.920	.025	.054	.589	.077	.167
	100	.842	.036	.075	.781	.051	.104	.938	.029	.062	.625	.079	.170
TIMBRE	0	.026	.015	.032	.397	.039	.080	.390	.063	.137	.405	.049	.105
	20	.158	.040	.085	.436	.044	.090	.435	.067	.145	.438	.060	.129
	40	.373	.064	.135	.481	.045	.091	.527	.053	.114	.435	.072	.155
	60	.737	.057	.120	.521	.047	.096	.601	.069	.150	.440	.058	.125
	80	.895	.027	.058	.586	.045	.093	.637	.057	.124	.536	.070	.151
	100	.965	.017	.036	.513	.047	.097	.607	.061	.132	.420	.065	.140

Note. *M* - Mean, *SE* – Standard Error of the Mean, *CI* – 95% Confidence Interval around the Mean), for each combination of morph type (MType) and morph level (ML).

*Note that ML50 was not included in the ANOVAs.

VOICE GENDER AND AGE PERCEPTION IN CI USERS

Table 4. Gender Experiment. Comparison of the 14 high performing CI users and the 19 normal hearing (NH) listeners.

	<i>df1</i>	<i>df2</i>	<i>F</i>	<i>p</i>	ϵ_{HF}	η^2_p
ANOVA comparing						
NH and high performing CI users						
ML	5	155	335.650	<.001		.915
MType x ML	10	310	16.845	<.001		.352
VCV x ML	5	155	3.116	.010		.091
PerfGroup x ML	5	155	9.992	<.001		.244
PerfGroup x MType	2	62	0.973	.384		.030
PerfGroup x VCV	1	31	13.120	.001		.297
PerfGroup x MType x ML	10	310	15.019	<.001		.326
PerfGroup x VCV x ML	5	155	5.328	<.001		.147
Post hoc ANOVA of the PerfGroup x MType x ML interaction						
separately per MType						
FullcT						
PerfGroup	1	31	0.319	.576		.010
ML	5	155	353.020	<.001	.661	.919
PerfGroup x ML	5	155	5.966	<.001	.661	.161
Timbre						
PerfGroup	1	31	0.025	.876		.001
ML	5	155	65.425	<.001	.804	.679
PerfGroup x ML	5	155	23.848	<.001	.804	.435
F0						
PerfGroup	1	31	1.106	.301		.034
ML	5	155	193.283	<.001	.792	.862
PerfGroup x ML	5	155	1.557	.175	.792	.048

Note. Top rows show main effects and interactions of the 3 x 2 x 6 x 2 ANOVA on the proportion of “female” responses with the factors Morph Type (MType: F0, FULLcT, TIMBRE), VCV syllable (VCV: aba, igi), Morph Level (ML: 0, 20, 40, 60, 80, 100) and a between-subject factor Performance Group (PerfGroup: NH, CI). Lower rows show the post hoc analyses separately per MType. Where indicated, the Huynh-Feldt Epsilon value ϵ_{HF} is given to adjust *p*-values.

VOICE GENDER AND AGE PERCEPTION IN CI USERS

Table 5. Gender Experiment. Comparisons of high performing CI users versus NH listeners.

MType	ML	Mean (SE)		Welch t-Test					Two sample t-Test			
		NH (N = 19)	CI users (n = 14)	<i>t</i>	<i>df</i>	<i>p</i>	<i>95CI</i>	<i>95CI</i>	<i>t</i> (31)	<i>p</i>	<i>95CI</i>	<i>95CI</i>
FullcT												
	0	.007 (.007)	.116 (.038)	2.830	13.8	.014*	.026	.193	3.275	.003*	.041	.178
	20	.022 (.012)	.143 (.051)	2.329	14.5	.035*	.010	.232	2.666	.012*	.028	.213
	40	.241 (.049)	.351 (.060)	1.431	27.3	.164	-.048	.268	1.442	.159	-.046	.265
	60	.842 (.047)	.708 (.051)	-1.925	29.0	.064	-.276	.008	-1.909	.066	-.277	.009
	80	.987 (.009)	.923 (.027)	-2.292	16.0	.036*	-.124	-.005	-2.571	.015*	-.115	-.013
	100	.993 (.007)	.946 (.025)	-1.801	14.8	.092	-.103	.009	-2.053	.049*	-.094	.000
F0												
	0	.046 (.022)	.071 (.025)	0.760	28.3	.453	-.043	.094	0.760	.453	-.043	.094
	20	.151 (.042)	.161 (.036)	0.171	31.0	.865	-.103	.121	0.163	.871	-.108	.127
	40	.382 (.048)	.348 (.069)	-0.397	24.5	.694	-.206	.140	-0.410	.684	-.199	.132
	60	.664 (.054)	.688 (.061)	0.283	28.7	.779	-.144	.190	0.281	.780	-.144	.190
	80	.776 (.047)	.920 (.025)	2.678	26.5	.013*	.033	.253	2.414	.022*	.022	.264
	100	.842 (.036)	.938 (.029)	2.092	30.9	.045*	.002	.188	1.978	.057	-.003	.194
TIMBRE												
	0	.026 (.015)	.390 (.063)	5.587	14.5	.000***	.224	.503	6.392	.000***	.248	.480
	20	.158 (.040)	.435 (.067)	3.529	22.0	.002**	.114	.439	3.723	.001**	.125	.428
	40	.373 (.064)	.527 (.053)	1.850	31.0	.074	-.016	.324	1.755	.089	-.025	.333
	60	.737 (.057)	.601 (.069)	-1.509	27.5	.143	-.320	.049	-1.518	.139	-.318	.047
	80	.895 (.027)	.637 (.057)	-4.054	18.9	.001**	-.391	-.125	-4.403	.000***	-.377	-.138
	100	.965 (.017)	.607 (.061)	-5.629	15.0	.000***	-.493	-.222	-6.399	.000***	-.472	-.244

Note. T-test statistics on unequal (Welch) and equal variances comparing high performing CI users (N = 14) with NH listeners (N = 19), and descriptive statistics (M; SE), separately per morph type (MType) and morph level (ML). Sign. = p <.001***, p <.01**, p <.05*.

VOICE GENDER AND AGE PERCEPTION IN CI USERS

Table 6. Age Experiment. Results of the Initial ANOVA and Post hoc Analyses.

	<i>df1</i>	<i>df2</i>	<i>F</i>	<i>p</i>	ϵ_{HF}	η^2_p
Initial ANOVA on all listeners (19 NH and 28 CI users)						
ML	1	45	174.511	<.001		.795
SpSex	1	45	11.437	.001		.203
MType x ML	3	135	90.503	<.001	.816	.668
LGroup x ML	1	45	51.276	<.000		.533
LGroup x SpSex	1	45	11.297	.002		.201
LGroup x MType x ML	3	135	30.697	<.001	.816	.406
LGroup x SpSex x ML	1	45	7.756	.008		.147
LGroup x SpSex x MType x ML	3	135	3.001	.033	.907	.063
Post hoc ANOVAs on ...						
... all NH listeners (<i>N</i> = 19)						
ML	1	18	206.687	<.001		.920
MType x ML	3	54	86.931	<.001	.801	.828
... all CI users (<i>N</i> = 28)						
ML	1	27	20.482	<.001		.431
SpSex	1	27	20.406	<.001		.430
MType x ML	3	81	11.090	<.001	.807	.291
SpSex x ML	1	27	5.825	.023		.177
SpSex x MType x ML	3	81	3.576	.017		.117

Note. Top rows show significant main effects and interactions of the 4 x 2 x 2 x 2 ANOVA on the proportion of “>50” responses with the factors Morph Type (MType: F0, FULL, TIMBRE, TIME), Speaker Sex (SpSex: female, male), Morph Level (ML: 0, 100) and a between-subject factor Listener Group (LGroup: NH, CI). Lower rows show post hoc analyses separately per LGroup. Where indicated, the Huynh-Feldt Epsilon value ϵ_{HF} is given to adjust *p*-values.

Table 7. Age-Experiment. Descriptive Statistics for NH listeners ($N = 19$), Cochlear Implant Users ($N = 28$), and for High and Low performing CI users ($n = 14$ each).

		Normal Hearing (N = 19)			CI Users (N = 28)			High Performing CI Users (N=14)			Low Performing CI Users (N=14)		
ML	MType	M	SE	CI	M	SE	CI	M	SE	CI	M	SE	CI
All Voices:													
0	FULL	.063	.034	.071	.355	.028	.057	.264	.037	.080	.446	.023	.049
0	TIMBRE	.139	.031	.066	.400	.027	.056	.335	.042	.091	.464	.027	.058
0	F0	.358	.037	.078	.454	.024	.050	.397	.049	.107	.493	.026	.057
0	TIME	.423	.028	.059	.445	.029	.060	.396	.037	.081	.512	.022	.048
100	TIME	.520	.034	.072	.509	.022	.045	.645	.040	.086	.411	.030	.066
100	F0	.703	.025	.052	.528	.033	.068	.521	.033	.072	.497	.029	.062
100	TIMBRE	.878	.024	.050	.616	.024	.049	.682	.030	.065	.550	.028	.060
100	FULL	.937	.025	.052	.611	.036	.074	.744	.035	.076	.478	.038	.081
Female Voices:													
0	FULL	.054	.028	.058	.166	.039	.079	.224	.067	.145	.107	.034	.074
0	TIMBRE	.160	.041	.087	.221	.039	.080	.286	.053	.115	.156	.053	.115
0	F0	.360	.052	.109	.247	.039	.080	.357	.051	.109	.136	.043	.093
0	TIME	.453	.032	.067	.331	.043	.089	.450	.056	.122	.212	.049	.106
100	TIME	.563	.066	.139	.348	.050	.102	.473	.065	.140	.222	.060	.130
100	F0	.651	.042	.089	.401	.054	.111	.640	.043	.092	.162	.040	.087
100	TIMBRE	.868	.044	.093	.476	.061	.126	.679	.061	.132	.273	.074	.160
100	FULL	.908	.038	.080	.510	.059	.120	.749	.053	.114	.270	.052	.113
Male Voices:													
0	FULL	.072	.041	.086	.545	.062	.127	.304	.058	.126	.786	.059	.128
0	TIMBRE	.117	.044	.093	.579	.050	.103	.385	.059	.127	.773	.035	.076
0	F0	.356	.051	.107	.661	.060	.123	.435	.066	.142	.888	.052	.113
0	TIME	.394	.061	.127	.559	.057	.116	.344	.067	.145	.774	.041	.089
100	TIME	.477	.037	.079	.671	.042	.086	.569	.056	.121	.773	.051	.110
100	F0	.755	.055	.116	.655	.037	.076	.649	.061	.133	.661	.044	.096
100	TIMBRE	.888	.027	.056	.756	.039	.079	.685	.050	.108	.828	.054	.116
100	FULL	.965	.017	.035	.712	.037	.077	.740	.062	.134	.685	.043	.092

Note. *M* - Mean, *SE* – Standard Error of the Mean, *CI* – 95% Confidence Interval around the Mean). Top: Results are shown for each combination of morph type (MType) and morph level (ML), separately for the listener groups. Middle and bottom: Results are also shown for each combination of MType, ML and speaker sex.

Table 8. Age Experiment. Comparison of the 14 high performing CI users and the 19 normal hearing (NH) listeners.

	<i>df1</i>	<i>df2</i>	<i>F</i>	<i>p</i>	ϵ_{HF}	η^2_p
ANOVA comparing						
NH and high performing CI users						
ML	1	31	267.523	<.001	.837	.896
SpSex	1	31	0.190	.666		.006
MType	3	93	3.559	.017	.864	.103
MType x ML	3	93	82.428	<.001	.837	.727
PerfGroup x ML	1	31	18.498	<.001		.374
PerfGroup x SpSex	1	31	0.169	.684		.005
PerfGroup x MType x ML	3	93	14.676	<.001	.837	.321
PerfGroup x SpSex x ML	1	31	1.525	.226		.047
PerfGroup x MType x SpSex x ML	3	93	2.582	.058		.077
Post hoc ANOVAs of the PerfGroup x MType x ML interaction						
Separately per MType						
Full						
PerfGroup	1	31	0.026	.873		<.001
ML	1	31	327.705	<.001		.914
PerfGroup x ML	1	31	27.666	<.001		.472
Timbre						
PerfGroup	1	31	0.000	.996		<.001
ML	1	31	239.214	.001		.885
PerfGroup x ML	1	31	31.386	.001		.503
F0						
PerfGroup	1	31	0.103	.750		.003
ML	1	31	60.201	<.001		.660
PerfGroup x ML	1	31	1.585	.217		.049
Time						
PerfGroup	1	31	0.079	.781		.003
ML	1	31	17.181	<.001		.357
PerfGroup x ML	1	31	0.270	.607		.009

Note. Top rows show main effects and interactions of the 4 x 2 x 2 x 2 ANOVA on the proportion of “>50 years” responses with the factors Morph Type (MType: F0, FULL, TIMBRE, TIME), Speaker Sex (SpSex: female, male), Morph Level (ML: 0, 100) and a between-subject factor Performance Group (PerfGroup: NH, CI). Lower rows show the post hoc analysis separately per Morph Type. Where indicated, the Huynh-Feldt Epsilon value ϵ_{HF} is given to adjust *p*-values.

Table 9. Descriptive statistics for deviations scores for three groups of participants as defined by the degree of satisfaction with the CI in everyday life situations.

CISatisfaction	<i>N</i>	<i>d_{gender}</i>				<i>d_{age}</i>			
		<i>M</i>	<i>SD</i>	<i>SE</i>	<i>CI</i>	<i>M</i>	<i>SD</i>	<i>SE</i>	<i>CI</i>
0 „not satisfied“	0	-	-	-	-	-	-	-	-
1 „less satisfied“	5	.427	.084	.037	.104	.503	.018	.008	.022
2 „satisfied“	16	.399	.085	.021	.045	.453	.048	.012	.026
3 „fully satisfied“	7	.355	.107	.040	.099	.399	.058	.022	.054

Note. (*M*, *SD*, *SE*, 95% *CI*) for deviations scores *d_{gender}*, and *d_{age}* for participants who reported to be (1) less satisfied, (2) satisfied, or (3) fully satisfied with their CI in everyday life situations. Note that no participant reported to be (0) not satisfied.

Collected Figure Legends

Figure 1. Gender Experiment. Mean proportion of “female” responses across morph levels, separately for all morph types (MType) and all 19 normal hearing (NH) (a) and all 28 CI users (b). Vertical bars indicate SEs.

Figure 2. Gender Experiment. Individual data. Proportion of “female” responses across morph levels, separately for all morph types (MType) and each individual listener. Note that 28 CI users were ranked according to d_{gender} , the gender-performance score (left), with 19 NH listeners also shown (right). For each CI user d_{gender} is given with participant gender (m=male, f=female), number, and age in years (yrs).

Figure 3. Gender Experiment. Mean proportion of “female” responses across morph levels, separately for (a) 14 high performing CI users and (b) 14 low performing CI users. (c) Comparison between groups (PerfGroup), i.e. high performing CI users and NH listeners; separately per morph type (MType: FullcT, F0, TIMBRE). Vertical bars indicate SEs.

Figure 4. Age Experiment. Mean proportion of old (“>50 years”) responses across morph levels and morph types (MType), separately for both female and male voices. Data is shown for 19 NH listeners (a), 28 CI users (b), and separately for high (c) and low (d) performing CI users. Vertical bars indicate SEs.

Figure 5. Age Experiment. Mean proportion of old (“>50 years”) responses across morph levels, separately for each morph type, comparing 14 high performing CI users with 19 NH listeners. Vertical bars indicate SEs.

Figure 6. Scatterplot depicting the correlation ($r = .592$, $p < .001$; Pearson, two-tailed) between the two performance deviation scores d_{gender} , and d_{age} . Note that lower scores reflect better performance.

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6