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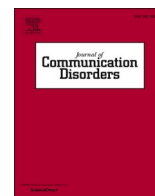
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Factors affecting talker discrimination ability in adult cochlear implant users

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ABSTRACT

Introduction: Real-world speech communication involves interacting with many talkers with diverse voices and accents. Many adults with cochlear implants (CIs) demonstrate poor talker discrimination, which may contribute to real-world communication difficulties. However, the factors contributing to talker discrimination ability, and how discrimination ability relates to speech recognition outcomes in adult CI users are still unknown. The current study investigated talker discrimination ability in adult CI users, and the contributions of age, auditory sensitivity, and neurocognitive skills. In addition, the relation between talker discrimination ability and multiple-talker sentence recognition was explored.

Methods: Fourteen post-lingually deaf adult CI users (3 female, 11 male) with ≥ 1 year of CI use completed a talker discrimination task. Participants listened to two monosyllabic English words, produced by the same talker or by two different talkers, and indicated if the words were produced by the same or different talkers. Nine female and nine male native English talkers were paired, resulting in same- and different-talker pairs as well as same-gender and mixed-gender pairs. Participants also completed measures of spectro-temporal processing, neurocognitive skills, and multiple-talker sentence recognition.

Results: CI users showed poor same-gender talker discrimination, but relatively good mixed-gender talker discrimination. Older age and weaker neurocognitive skills, in particular inhibitory control, were associated with less accurate mixed-gender talker discrimination. Same-gender discrimination was significantly related to multiple-talker sentence recognition accuracy.

Conclusion: Adult CI users demonstrate overall poor talker discrimination ability. Individual differences in mixed-gender discrimination ability were related to age and neurocognitive skills, suggesting that these factors contribute to the ability to make use of available, degraded talker characteristics. Same-gender talker discrimination was associated with multiple-talker sentence recognition, suggesting that access to subtle talker-specific cues may be important for speech recognition in challenging listening conditions.

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1. Introduction

Cochlear implants (CI) have been successful in providing a restored sense of hearing and improved speech recognition to adults with severe-to-profound hearing loss (HL), with many post-lingually deafened adult CI users able to achieve good speech recognition skills in quiet listening conditions (Rouger et al., 2007). Yet, real-world listening often involves adverse and challenging conditions, characterized by noise or other sources of signal degradation, as well as the vast amount of acoustic-phonetic variability from multiple talkers with diverse linguistic backgrounds and experiences (e.g., Gilbert et al., 2013; Mattys et al., 2012; Pisoni, 1997). Normal-hearing (NH) individuals are able to rapidly adjust and compensate to changes in the vocal sound source, facilitated by their ability to perceive, encode, and retain in memory detailed talker information (Nygaard & Pisoni, 1998; Nygaard et al., 1994). Learning talker-specific patterns in speech promotes the robust recognition of speech (Nygaard & Pisoni, 1998; Nygaard et al., 1994). Moreover, detailed talker information can be used by NH listeners to identify a familiar talker or make explicit judgements about a talker, such as his/her gender (e.g., Lass et al., 1976) or region of origin (Labov, 1972).

1.1. Speech recognition and talker variability in adult CI users

Real-world conditions can be challenging for CI users, who receive input signals that are highly degraded in spectro-temporal detail due to limitations of the electrode-nerve interface and relatively broad electrical stimulation of the auditory nerve (for a review, see Başkent et al., 2016). CI users achieve relatively poorer recognition of words and sentences produced by multiple talkers with distinct voices and accents compared to a single talker (e.g., Ji et al., 2014; Kopolowicz et al., 2020; Sommers, 1997; Tamati et al., 2020a). Further, adaptation to an unfamiliar talker or accent is impaired in CI users (Kopolowicz et al., 2020). Studies using noise-vocoding to simulate CI hearing have additionally shown that the ability to adapt to a single talker or rapidly adapt to trial-to-trial changes in talkers' voices are impacted by limitations in CI hearing (Kopolowicz et al., 2018; Tamati et al., 2020b). Together, these studies suggest that CI users have difficulty adapting to and recognizing challenging speech produced by multiple talkers and accents. However, significant variability exists within CI users' speech recognition abilities in both favorable (Beyea et al., 2016; Holden et al., 2013; Lazard et al., 2012) and challenging conditions (Rodman et al., 2020).

1.2. Talker discrimination in adult CI users

Limitations in the perception of talker details in CI users may relate to speech recognition difficulties in challenging listening conditions. The perception of talker details relies on the perception of several talker voice cues, including vocal pitch (related to fundamental frequency, F0) and formant frequency information (related to vocal tract length, VTL; Smith & Patterson, 2005). In CI users, while reduced spectral resolution is likely due in part to channel overlap from broad stimulation across electrodes (Stickney et al., 2006), coding of temporal fine structure that provides detailed voice cues may be limited by the refractory period of the nerve itself (Rubinstein & Hong, 2003). Additionally, modern CI processing strategies optimize transmission of temporal envelope information at the cost of temporal fine structure (Moon & Hong, 2014). Such limitations hinder the transmission of talker-specific characteristics such as F0 and vocal tract length information (e.g., Fitch & Giedd, 1999; Gaudrain & Başkent, 2015, 2018), and likely limit the information available to be used in talker perception. As a result, CI users demonstrate a relative deficit in perception of detailed talker information in speech. For example, CI users demonstrate poor talker discrimination, particularly when discriminating different talkers of the same gender (Cleary & Pisoni, 2002; Cleary et al., 2005; Massida et al., 2011; Osberger et al., 1991). Moreover, while CI users are generally able to achieve some talker discrimination between male and female talkers (e.g., Massida et al., 2011; Massida et al., 2011), where voice cue differences may be greater, they do so abnormally by showing different weighting of voice cues compared to NH listeners, relying more heavily on fundamental frequency cues and less so on vocal tract length than their NH peers (Fuller et al., 2014). Similarly, CI users show poor discrimination of other sources of talker variability, including a talker's region of origin and foreign accent (e.g., Clopper & Pisoni, 2004; Hay-McCutcheon et al., 2018; Tamati et al., 2014, 2021a).

CI users also show vast individual differences in the discrimination of talker details (Hay-McCutcheon et al., 2018; Tamati et al., 2021a). Further, recent studies have demonstrated a close link between recognition of high-variability speech and the perception of talker details in adult NH listeners and CI users (Tamati et al., 2021a, 2013), whereby listeners who demonstrate good perception of talker details also show more accurate speech recognition. In particular, Tamati et al. (2021a) found that prelingually deaf CI users who demonstrated stronger perception of talker details also showed more accurate sentence recognition skills, across a wide range of challenging materials, including speech with high talker and accent variability. These results as well as previously demonstrated variability in CI users' sensitivity to individual voice cues (Gaudrain & Başkent, 2018) suggest that individual CI users vary in the perception and encoding of fine-grained acoustic-phonetic details that may affect the perception of talker details as well as speech recognition in challenging conditions.

1.3. Individual differences in talker discrimination

Although it has been shown that CI users have relatively poorer talker discrimination abilities than NH individuals (Mühler et al., 2009), our understanding of the factors contributing to poor discrimination ability is still limited. Previous research suggests that aging, and associated changes in bottom-up auditory processes and top-down neurocognitive functioning, may impact speech recognition abilities in adult CI users. Access to relevant talker-specific cues is crucial for accurate talker discrimination. As reviewed above, the CI device poorly conveys important voice cues. However, previous work has also suggested that CI users may vary

substantially in the voice cues available to them (Gaudrain & Başkent, 2015). Age-related declines in auditory sensitivity may contribute to individual differences in talker discrimination. In NH individuals, advancing age has been shown to impair temporal processing abilities, resulting in poorer consonant distinction (Goupell et al., 2017) as well as poorer gender identification under conditions of spectral degradation (Schvartz & Chaterjee, 2012). Further, the effect of aging on temporal processing may be even more detrimental to speech recognition in hearing-impaired listeners (Gordon-Salant et al., 2006), and more so for CI users (Shader et al., 2020), who rely heavily on temporal cues in speech perception due to poor spectral resolution. Age has also been shown to affect F0 perception. In a study of NH listeners, Vongpaisal and Pichora-Fuller identified an age-related decline in F0 discrimination (Vongpaisal & Pichora-Fuller, 2007). Souza and colleagues described a similar finding and ascribed it to age-related deficits in perception of periodicity, which represents F0 information (Souza et al., 2011). Older NH listeners have also been shown to have worse spectral resolution, thereby mediating a relationship between advancing age and poor speech recognition (Moberly et al., 2018b). Lastly, aging may be associated with poorer spiral ganglion neuron integrity and differences in the electrode-neuron interface among CI users (DiNino et al., 2019; Jahn & Arenberg, 2020), which may impact older CI listeners' access to talker-specific cues. In summary, it is very likely that aging would impact individual CI users' access to important cues for talker discrimination.

Neurocognitive aging has been associated with speech perception deficits, and in particular deficits in talker perception. While long-term memory is well preserved in age, short-term and working memory abilities worsen (Pichora-Fuller, 2003). Although not examining talker discrimination, studies of CI users have shown that age and neurocognitive skills are related to speech recognition (Moberly et al., 2018b). In experienced CI users, older age at testing or implantation have both been correlated with less accurate open-set speech recognition scores (Beyea et al., 2016; Mahmoud & Ruckenstein, 2014; Moberly et al., 2018b; Williamson et al., 2009). Measures of neurocognitive functions, including non-verbal reasoning, inhibitory control, and speed of lexical access, have also been shown to be correlated with speech recognition in adult CI users as well as older NH peers listening to spectrally degraded speech (Schvartz et al., 2008), at least partially mediating the relationship between older age and poorer speech recognition abilities (Moberly et al., 2018b). Research in NH listeners further suggests a role for neurocognitive skills in talker discrimination. Older NH adults have been reported to demonstrate greater difficulty with learning talkers' voices as compared with younger NH peers (Pichora-Fuller, 2003). Further, evidence has suggested that age-related changes in neurocognitive functions contribute to worse speech understanding, specifically affecting the ability to adapt to talker variability (Sommers, 1997). Aging may similarly detrimentally impact talker discrimination abilities in adult CI users, through age-related changes in top-down neurocognitive functioning.

2. The current study

The aim of the current study was to investigate talker discrimination in higher-performing adult CI users, and to determine the relative contributions of age, bottom-up auditory skills, and top-down neurocognitive skills on talker discrimination abilities. Experienced CI users with greater than one year of CI use completed a talker discrimination task in which they determined if two utterances were produced by the same or different talkers. Talker pairs consisted of both same-gender and mixed-gender talker pairs, since previous studies have suggested relatively good talker discrimination across genders. This study enrolled only relatively high-performing CI users with good speech recognition abilities (i.e., isolated word recognition scores > 65%), since previous studies have suggested that the role of neurocognitive skills in speech processing may depend on the quality of the signal delivered by the CI (Bhargava et al., 2016; Tamati et al., 2020a) and/or baseline perceptual abilities (Rodman et al., 2020). In other words, CI users with very poor bottom-up abilities may be unable to deploy neurocognitive skills effectively to enhance speech processing. Thus, inclusion of only relatively high-performing CI users permits evaluation of the contribution of neurocognitive functions to individual differences in talker discrimination ability.

We predicted that CI users would demonstrate overall poor talker discrimination, specifically for same-gender talkers with relatively better mixed-gender talker discrimination, consistent with previous findings (e.g., McDonald et al., 2003; Osberger et al., 1991; Tamati et al., 2020b). As such, we sought to replicate the earlier findings on talker discrimination in higher-performing adult CI users. To investigate the potential factors impacting talker discrimination abilities in this group of high-performing, experienced CI users, we first determined the association of talker discrimination performance with age. To further understand any potential relation between age and talker discrimination abilities, we investigated whether bottom-up or top-down skills might drive any aging effect on talker discrimination. Bottom-up auditory skills were measured using the Spectral-Temporally Modulated Ripple Test (SMRT; Aronoff & Landsberger, 2013), a behavioral test of spectro-temporal processing. Several neurocognitive functions were measured including working memory capacity, inhibitory control, speed of lexical access, and nonverbal reasoning. Given previous findings in NH listeners, we hypothesized that increasing age would be associated with worse talker discrimination. We further predicted that CI users with better performance on tasks assessing bottom-up auditory and top-down neurocognitive skills would achieve more accurate talker discrimination. However, the relative roles of these skills were expected to differ depending on the talker pair. More specifically, auditory skills should contribute more to individual differences in same-gender talker discrimination, for which the highly detailed voice cues might not be available to all CI users. In contrast, neurocognitive skills should contribute more in the mixed-gender conditions, where cognitive compensatory mechanisms may help CI users make better use of more disparate talker cues. Finally, we predicted that talker discrimination ability (i.e., better access to talker-specific information) would be associated with speech recognition ability using high-variability sentence materials.

3. Methods

3.1. Participants

Fourteen post-lingually deafened adult CI users, all with greater than one year of CI experience, participated in the current study. Participants (3 female, 11 male) were between 39 and 87 years old, with a mean of 67 years ($SD=14$). Mean duration of deafness prior to implantation (computed as age at implantation minus participant-reported age at onset of hearing loss) was 24 years ($SD=14$), and mean duration of CI use was 7.2 years ($SD=4.0$). Seven participants were bilateral CI users, five were unilateral CI users with contralateral hearing aid use, and two were unilateral CI users with no contralateral hearing aid use. Additionally, all were noted to be high-performing CI users, with isolated word recognition scores of 66–94%, mean 80 ($SD=8.6\%$) on consonant-nucleus-consonant words (CNC word test; Peterson & Lehiste, 1962) in the best-aided binaural condition with participants using their everyday listening devices. All participants passed a Mini-Mental Status Exam (MMSE), presented using written instructions, with a raw score ≥ 26 . Finally, all CI users were part of a larger ongoing study on speech recognition outcomes in adult CI users (Kramer et al., 2018; Moberly et al., 2018a, 2018b). Additional participant demographics are provided in Table 1.

3.2. General approach and measures

Participants were tested using their standard hearing devices (one CI, two CIs, or one CI with contralateral hearing aid if typically worn) to capture their everyday listening conditions. Auditory stimuli in the talker discrimination task were presented free field at 70 dB SPL via a Roland MA-12C loudspeaker (Roland Corp, Los Angeles, CA) placed one meter from the participant at 0° azimuth. Individual measures of spectro-temporal processing, neurocognitive functioning, and sentence recognition were taken from the larger study on speech recognition outcomes (Kramer et al., 2018; Moberly et al., 2018a, 2018b). All measures were collected within twelve months prior to talker discrimination testing. All testing was carried out in a sound-proof booth or an acoustically insulated testing room. All participants provided informed written consent prior to participation and received \$15 per hour for their time. Institutional Review Board (IRB) approval was obtained.

3.3. Talker discrimination task

Participants completed an AX same-different talker discrimination task, using monosyllabic English words produced by nine female and nine male talkers from the PB/MRT Word Multi-talker Speech Database, based on the Phonetically Balanced words (PB; Egan, 1948) and Modified Rhyme Test (MRT, House et al., 1965). The average F0 for female talkers ranged from 118 to 251 Hz (individual female talkers' average F0: 188, 193, 195, 201, 212, 222, 236, 242, and 251 Hz). The average F0 for male talkers ranged from 109 to 151 Hz (individual male talkers' average F0: 109, 111, 115, 118, 126, 133, 134, 141, and 151 Hz). The task consisted of presentation of two words, separated by 1000 ms; the participant was asked to indicate whether the words were produced by the 'Same' or 'Different' talkers by key press (Same=1; Different=0). A total of 216 words were selected from the database. Out of the 216 words, 23 were selected for each talker. Although some words were repeated across talkers (1–6 repetitions across talkers), all word pairs were unique, and words were not repeated within a trial.

The task consisted of two Talker Conditions (Same, Different) and three Gender Conditions (Female, Male, Mixed). For Talker Conditions, Same-talker trials included trials with target words produced by the same talker; Different-talker trials included trials with target words produced by two different talkers. For Gender Conditions, Female-talker trials included trials for which both talkers were female, while Male-talker trials included trials for which both talkers were male. Finally, Mixed-gender trials included trials for which one talker was female and one talker was male. All possible combinations of the 20 talkers, in both possible orders, were presented, as

Table 1
Participant demographics and hearing history.

Participant Number	Sex	Age (years)	Age at Implantation (years)	Duration of Deafness (years)	Implant Side	Implant Brand	Hearing aid usage	CNC (% correct)	Better ear PTA (dB HL)
1	F	68	54	13	Bilateral	Cochlear	N/A	80	120
2	M	58	50	29	Bilateral	Cochlear	N/A	88	120
3	M	63	57	2	Bilateral	Cochlear	N/A	94	120
4	M	81	72	16	Bilateral	Cochlear	N/A	80	120
5	M	87	76	26	Right	Cochlear	Yes	72	68.75
6	M	70	60	46	Left	Cochlear	No	92	80
7	F	39	31	15	Left	Cochlear	Yes	86	116.25
8	M	63	55	3	Right	Cochlear	Yes	76	111.25
9	M	56	48	50	Bilateral	Cochlear	N/A	70	120
10	M	85	82	32	Bilateral	Cochlear	N/A	70	78.00
11	F	70	66	unknown	Bilateral	Cochlear	N/A	86	120
12	M	69	68	26	Left	Cochlear	Yes	82	83
13	M	63	60	unknown	Left	Cochlear	Yes	66	112.5
14	M	75	73	33	Right	Cochlear	Yes	88	66

Note: CNC: Consonant Nucleus Consonant; PTA: unaided pure tone average across 0.5, 1, 2, and 4 kHz.

well as six repetitions of each Same-talker pair. Therefore, the task consisted of 108 Same-talker trials (54 Female, 54 Male) and 306 Different-talker trials (72 Female, 72 Male, 162 Mixed), for a total of 414 trials. Responses for each trial were recorded and examined for accuracy by Talker Condition and Gender Condition.

3.4. Spectro-temporal processing

Participants' spectro-temporal processing was assessed using the Spectral-Temporally Modulated Ripple Test (SMRT; Aronoff & Landsberger, 2013). Stimuli are 202 pure-tone frequency components, modulated by a sine wave at different ripple densities. The task consisted of a three-interval, two-alternative forced-choice task in which two of the intervals contained a reference signal with 20 ripples per octave (RPO) and one contained the target signal. The target signal was initially set at 0.5 RPO and was modified using a one-up/one-down adaptive procedure with a step size of 0.2 RPO. Participants were asked to determine the reference from the target stimuli. A ripple-detection threshold was calculated based on the last six reversals of each run, with the first three runs discarded as practice. A higher score represents better spectro-temporal processing.

3.5. Neurocognitive functioning

Participants completed a battery of non-auditory neurocognitive measures, assessing working memory capacity, inhibitory control, speed of lexical access, and non-verbal reasoning. Measures of neurocognitive function were selected for the current study based on theoretical contributions of the perception of degraded speech, as well as previous findings demonstrating associations with speech recognition in adult CI users (e.g., Moberly et al., 2018b; Moberly, Castellanos, Vasil, Adunka, & Pisoni, 2018a; Moberly et al., 2016, 2018a, 2018b; Tamati et al., 2020a, 2021b). Visually presented measures were used to avoid the confounding issue of audibility.

3.5.1. Working memory capacity

Visual digit span was assessed using a modified version of the Wechsler Intelligence Scale for Children, Fourth Edition, Integrated (Wechsler, 2004). This measure, or very similar digit span measures of working memory capacity, have been used extensively in adult CI users (Anzivino et al., 2019; Moberly & Reed, 2019; Moberly et al., 2018a, 2018b). Participants were presented with a sequence of numerical digits on a screen, one digit at a time, and asked to recall the sequence by touching the digits in the correct serial order on a touch screen monitor. The score was calculated based on the total number of correct items.

3.5.2. Inhibitory control

A computerized Stroop Color-Word Interference test (<http://www.millisecond.com>) was used to evaluate inhibitory control, based on the original Stroop task (Stroop, 1935). Participants were presented with a color word with font in either the same (congruent trials, e.g., "red" presented in red font) or a different color (incongruent trials, e.g., "red" presented in blue font). The participant was then asked to press a key corresponding to the font color of the word shown. Response times for incongruent trials were used as a measure of inhibitory control. Note that stronger inhibitory control is reflected in lower scores.

3.5.3. Speed of lexical access

The Test of Word Reading Efficiency, version 2 (TOWRE-2, Torgesen, Wagner, & Rashotte, 2012) was used to assess speed of lexical access. Participants completed the TOWRE-2 Sight Word Efficiency subtest in which they read as many real words as possible in 45 s from a 108-word list (Form A). Percent words correctly read was used in analyses.

3.5.4. Nonverbal reasoning

The Raven's Progressive Matrices test (Raven, 2020) was used to measure nonverbal reasoning. Participants were presented with incomplete visual patterns on a touch screen monitor and asked to complete the visual pattern by selecting the best option from a set of alternatives. Participants completed as many items as possible in 10 min, and the total number of correct items was recorded and used in analyses.

3.6. Multiple-talker sentence recognition

Sentence Recognition was assessed using the PRESTO sentences (Gilbert et al., 2013), which was developed to assess high-variability sentence recognition and includes multiple male and female talkers with diverse regional accents. Scores were based on 32 PRESTO sentences, originally selected from the TIMIT (Texas Instruments/Massachusetts Institute of Technology) speech corpus (Garofolo et al., 1993). Original PRESTO sentence lists were balanced for talker gender, keyword frequency, and keyword familiarity, with no repeated talkers. For the current study, participants completed 2 practice trials and 30 test trials, repeating back the target sentences to the best of their ability. Scores were calculated as percent keywords correct in the final 30 sentences.

3.7. Data analyses

To assess talker discrimination performance abilities in higher-performing adult CI users, performance on the talker discrimination task was analyzed using a logistic mixed effects model in R (v3.6.2, R Core Team, 2019), utilizing the *glmer* function of the *lme4* package (v.1.1.21, Bates et al., 2015), with accuracy on each trial (1=correct response; 0=incorrect response) as the dependent

variable. Fixed factors (dummy coded) included Talker Identity (Same, Different) and Gender (Female, Male, Mixed). Participant was included as a random effect. Because Gender conditions were not equivalent for each Talker Identity (i.e., mixed-gender pairs only appeared for Different-talker pairs), we used a model that did not allow any fixed interaction effect between lexical difficulty and word status, and instead used a random interaction. Analysis started with a full-factorial model, and a series of model comparisons was completed using backward stepwise selection to determine the contribution to the model fit using the likelihood-ratio test. The change in model fit from removing a fixed effect was determined with ANOVA Chi-Square tests. Interactions were then detailed by fitting similar models to subsets of data. To explore significant main effects, post-hoc Tukey tests were run using the `glht` function in the `multcomp` package (Hothorn et al., 2008).

To assess individual differences in talker discrimination ability, three separate measures were calculated from the talker discrimination data: (1) Global talker discrimination ability, calculated as percent correct performance across all trials, (2) Same-gender talker discrimination ability, calculated as d' (d -prime) scores based on all same-gender trials (Female, Male) in both Talker Identity conditions (Same, Different), and (3) Mixed-gender talker discrimination ability, calculated as percent correct performance on mixed-gender trials in the Different-talker condition. The d' scores were used as a measure of Same-gender talker discrimination to account for possible response biases, and were calculated based on the hit and false alarm rate (Macmillan & Creelman, 2005). Performance was found to be near chance on same-gender trials, including both Same-talker and Different-talker pairs. Further investigation revealed that accuracy scores were strongly negatively correlated between the two conditions ($r = -0.76, p = 0.001$). This suggests that participants demonstrated possible bias towards responding same or different, which resulted in higher accuracy in either the Same- or Different-talker conditions.

Correlational analyses were carried out between these three primary measures and age, SMRT scores, and neurocognitive scores using one-tailed non-parametric Spearman's rank-order correlations. One-tailed correlation tests were used based on the consistent prediction that better talker discrimination abilities in adult CI users would be associated with better spectro-temporal processing and neurocognitive abilities, as well as more accurate multiple-talker sentence recognition scores on PRESTO. Non-parametric tests (i.e., one-tailed Spearman's rank-order correlations) were used to account for non-normality in the distribution of the study measures. For all measures, an alpha of 0.05 was set. When $p > 0.05$, correlations are reported as *not significant*. For the correlational analyses, the False Discovery Rate (FDR) correction was used for multiple comparisons; corrected p are reported.

4. Results

4.1. Group performance

Group performance on all tasks is summarized in Table 2. Fig. 1 shows talker discrimination performance by Talker Identity (left panel) and Gender (right panel). Both main effects of Talker Identity ($\chi^2(1) = 16.88, p < 0.001$) and Gender ($\chi^2(2) = 28.11, p < 0.001$) significantly improved the model fit. The full results of the model can be found in Table 3. As shown in Fig. 1, CI users were more accurate on Different-talker pairs compared to Same-talker pairs. Further, they were more accurate on Mixed gender pairs compared to both Female and Male pairs. For the main effect of Talker Identity, post-hoc Tukey tests confirmed that CI users were significantly more accurate on Different-talker pairs compared to Same-talker pairs ($p < 0.001$). For Gender, post-hoc Tukey tests confirmed that CI users were also significantly more accurate on Mixed gender pairs compared to both Female and Male pairs (all p 's < 0.001), and more accurate on Male pairs compared to Female pairs ($p = 0.01$).

Fig. 2 shows talker discrimination accuracy by Gender for Same-talker pairs (left) and Different-talker pairs (right). To explore the interaction between Talker Identity and Gender, separate analyses were conducted on the effect of Gender for both Same-talker and Different-talker pairs. For Same-talker pairs only, the main effect of Gender did not improve model fit ($\chi^2(1) = 1.73, p = 0.19$). However, for Different-talker pairs only, the main effect of Gender improved model fit ($\chi^2(2) = 17.23, p < 0.001$). Post-hoc Tukey tests confirmed that CI users were also significantly more accurate on Mixed gender pairs compared to both Female and Male pairs (all p 's < 0.001), and more accurate on Male pairs compared to Female pairs ($p = 0.01$). Thus, the effect of Gender on accuracy appears to be mainly driven by greater accuracy for mixed-gender pairs compared to same-gender pairs (either Female or Male) in the Different-

Table 2

Summary of performance on the talker discrimination task and on measures of spectro-temporal processing, neurocognitive skills, and multiple-talker sentence recognition.

Measure	Mean (SD)	Range
Talker Discrimination Accuracy- All Conditions (% correct)	71.30 ± 5.62	63.29–80.92
Talker Discrimination Accuracy- Mixed-Gender (% correct)	94.91 ± 5.62	83.95–100.00
Talker Discrimination –Same-Gender (d' score)	0.46 ± 0.42	–0.20–1.38
Inhibitory Control (Stroop; ms)	1497.81 ± 570.71	1002.18–3074.86
Working Memory (Digit Span)	45.93 ± 19.89	14.00–83.00
Speed of Lexical Access (TOWRE)	83.64 ± 9.31	67.00–99.00
Nonverbal Reasoning (Raven's)	12.64 ± 5.24	2.00–20.00
Spectro-temporal Processing (SMRT)	2.85 ± 1.37	0.73–5.10
MT Sentence Recognition (PRESTO;% Correct)	69.88 ± 13.01	47.58–86.61

Note: TOWRE: Test of Word Reading Efficiency; SMRT: Spectral Temporally Modulated Ripple Test; MT = Multiple-talker; PRESTO: Perceptually Robust English Sentence Test.

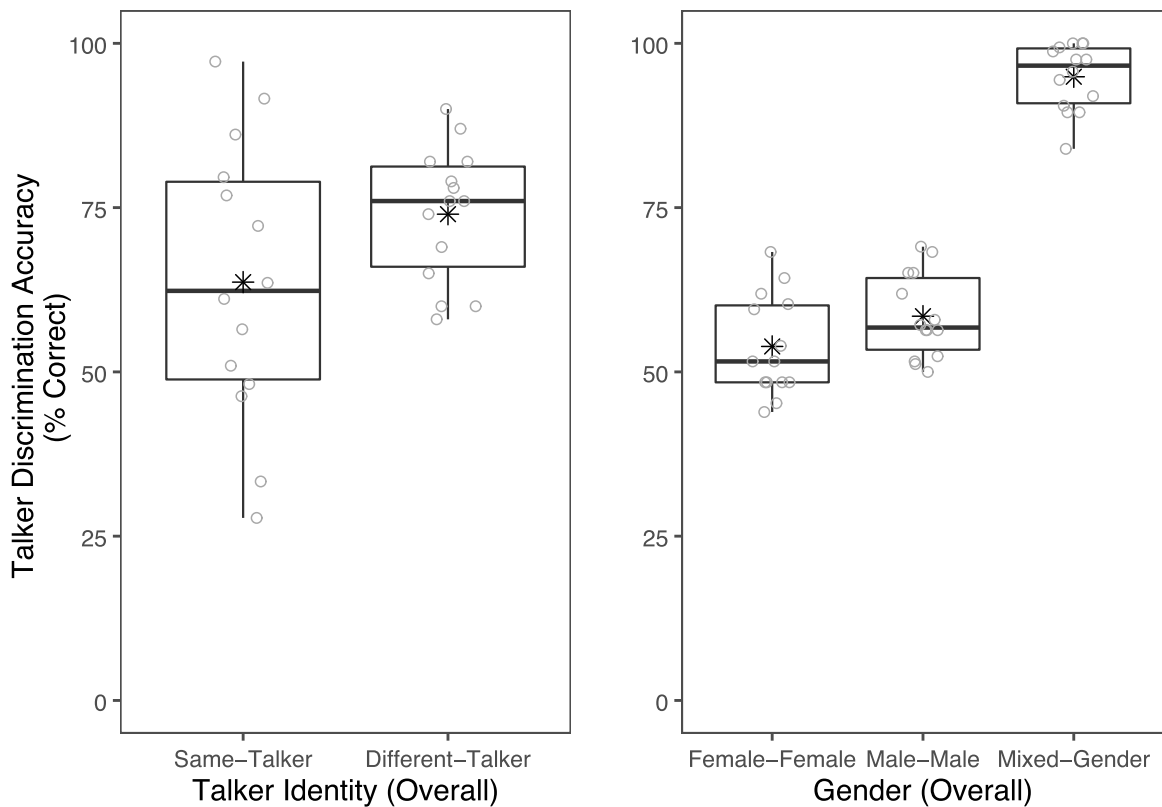


Fig. 1. Box plot showing talker discrimination accuracy (% correct) by Talker Identity (left) and Gender (right). The boxes extend from the lower to the upper quartile (the interquartile range, IQ), the solid midline indicates the median, and the star indicates the mean. The open gray circles indicate individual scores. The whiskers indicate the highest and lowest values no greater than 1.5 times the IQ, and the plus signs indicate outliers, which are defined as data points larger than 1.5 times the IQ.

Table 3
Results from logistic mixed effects models.

3a. Global model					
Predictor	Level	Coefficient	Error	z value	p value
Intercept		2.59	0.13	20.62	<0.001
Talker Identity	Different	ref			
	Same	0.50	0.07	7.62	<0.001
Gender	Mixed	ref			
	Male	-2.47	0.09	-26.47	<0.001
	Female	-2.66	0.09	-28.50	<0.001
3b. Effect of Gender on Same-Talker pairs only					
Predictor	Level	Coefficient	Error	z value	p value
Intercept		0.86	0.29	2.92	<0.001
Gender	Male	ref			
	Female	-0.16	0.11	-1.47	.0141
3b. Effect of Gender on Different-Talker pairs only					
Predictor	Level	Coefficient	Error	z value	p value
Intercept		2.79	0.23	11.97	<0.001
Gender	Mixed	ref			
	Male	-2.71	0.11	-25.54	<0.001
	Female	-2.97	0.11	-27.77	<0.001

talker condition.

4.2. Individual differences

4.2.1. Age

Correlational analyses were carried out between the three talker discrimination metrics and age. Results are displayed in [Table 4](#).

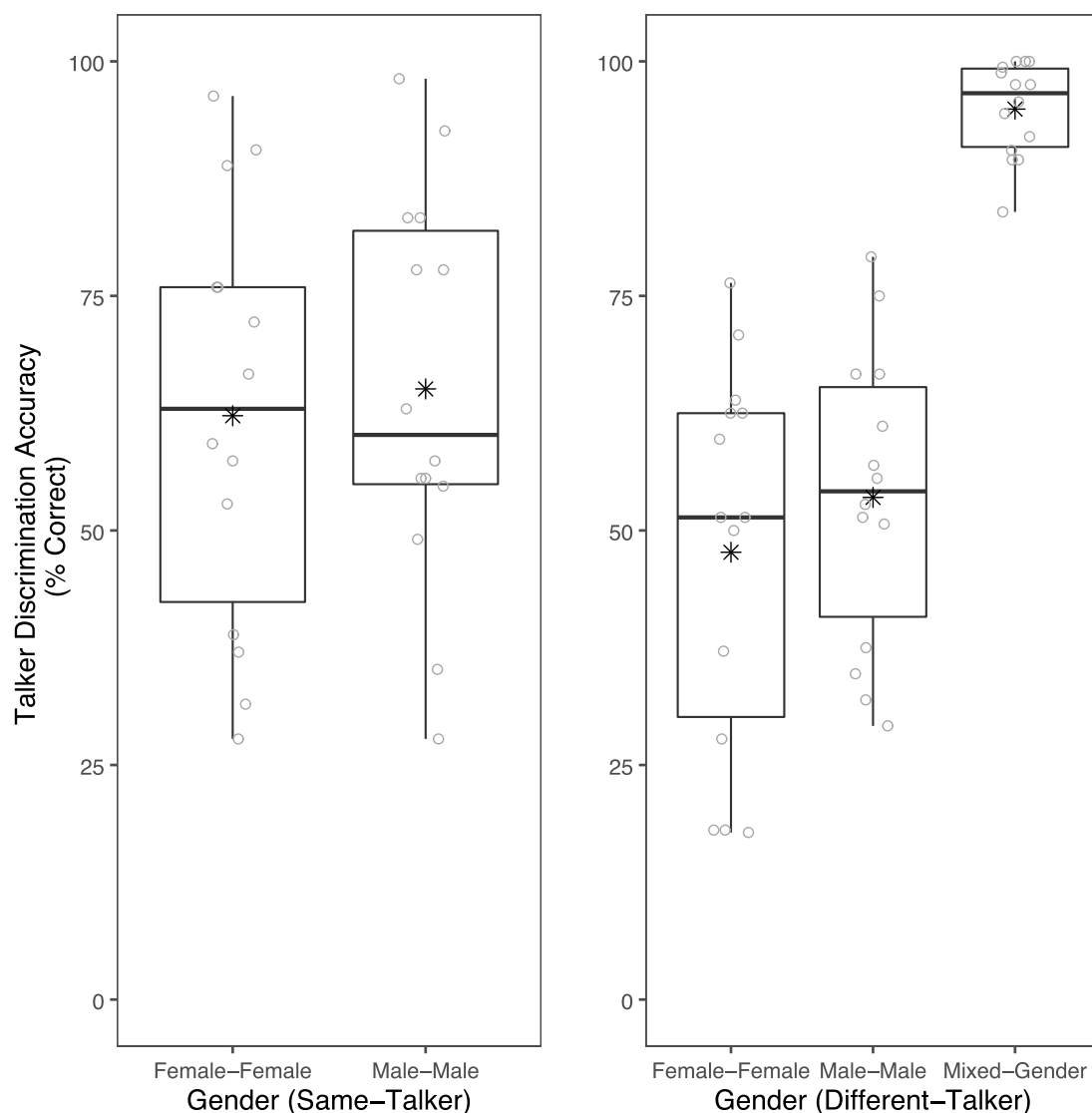


Fig. 2. Box plot showing talker discrimination accuracy (% correct) by Gender for Same-Talker (left) and Different-Talker Pairs (right). The boxes extend from the lower to the upper quartile (the interquartile range, IQ), the solid midline indicates the median, and the star indicates the mean. The open gray circles indicate individual scores. The whiskers indicate the highest and lowest values no greater than 1.5 times the IQ, and the plus signs indicate outliers, which are defined as data points larger than 1.5 times the IQ.

Age was significantly negatively correlated with Global talker discrimination ability ($r_s = -0.72, p = 0.007$) and Mixed-gender talker discrimination ability ($r_s = -0.62, p = 0.032$), shown in Fig. 3. Age was not significantly related to Same-gender talker discrimination ability. Thus, older CI users showed poorer Global and Mixed-gender talker discrimination accuracy than younger CI users.

4.2.2. Spectro-temporal processing

Correlational analyses were carried out between SMRT scores and the three talker discrimination metrics to examine the role of spectro-temporal processing in talker discrimination. Results are displayed in Table 4. SMRT scores were not significantly related to any measure of talker discrimination ability. Global talker discrimination ability ($r_s = 0.42, p = 0.098$) and Same-gender talker discrimination ability ($r_s = 0.37, p = 0.333$) were weakly correlated with spectro-temporal processing, but the correlations did not reach significance.

4.2.3. Neurocognitive functioning

Correlational analyses were carried out between the three talker discrimination metrics and working memory capacity (digit span), inhibitory control (Stroop), speed of lexical access (TOWRE-2), and nonverbal reasoning (Raven's Progressive Matrices). Results are displayed in Table 4. Working memory capacity was not related to any talker discrimination metric. Inhibitory control was

Table 4

Spearman's rank-order correlations between talker discrimination metrics and age, neurocognitive functioning, spectro-temporal processing, and multiple-talker sentence recognition.

Condition		Age	Inhibitory Control (Stroop)	Working Memory (Digit Span)	Speed of Lexical Access (TOWRE)	Nonverbal Reasoning (Raven's)	Spectro-temporal Processing (SMRT)	MT Sentence Recognition (PRESTO)
Talker Discrimination Accuracy– All Conditions (% correct)	r_s	-0.72	-0.79	0.03	0.59	0.53	0.42	0.39
	p	0.007	<0.001	0.458	0.031	0.044	0.098	0.100
Talker Discrimination Accuracy– Mixed-Gender (% correct)	r_s	-0.62	-0.74	0.11	0.46	0.26	0.17	0.14
	p	0.032	0.007	0.359	0.114	0.329	0.359	0.359
Talker Discrimination– Same-gender (d' score)	r_s	0.15	-0.08	-0.11	0.06	0.13	0.37	0.66
	p	0.417	0.417	0.417	0.417	0.417	0.333	0.035

Note: Bolded comparisons are significant after FDR correction. TOWRE: Test of Word Reading Efficiency; SMRT: Spectral Temporally Modulated Ripple Test; MT = Multiple-talker; PRESTO: Perceptually Robust English Sentence Test.

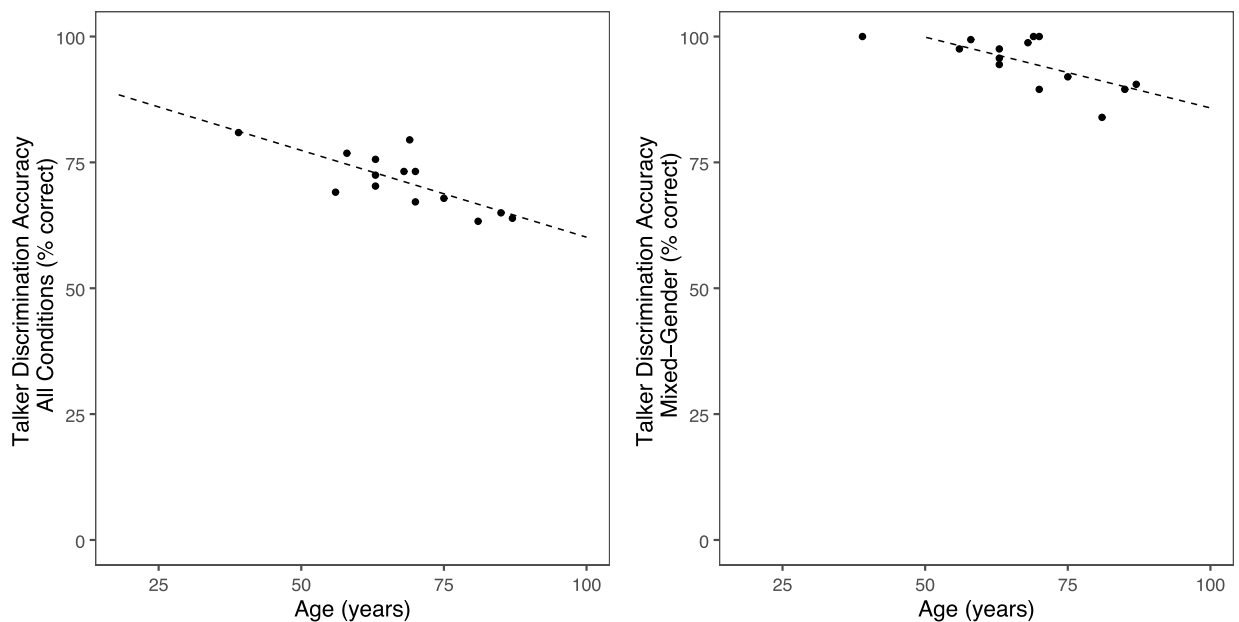


Fig. 3. Scatterplots showing the relation between Global talker discrimination ability (% correct) and age (left) and Mixed-gender talker discrimination ability (% correct) and age (right).

significantly negatively correlated (i.e. shorter response times on the Stroop were associated with better discrimination performance) with both Global talker discrimination ability ($r_s = -0.79$, $p < 0.001$) and Mixed-gender talker discrimination ability ($r_s = -0.74$, $p = 0.007$), shown in Fig. 4. Inhibitory control was not significantly related to Same-gender talker discrimination. Speed of lexical access was moderately related to both Global talker discrimination ($r_s = 0.59$, $p = 0.031$) and Mixed-gender talker discrimination ($r_s = 0.46$, $p = 0.114$), but not to Same-gender talker discrimination. However, only the correlation with Global talker discrimination ability reached significance. Nonverbal reasoning was moderately and significantly related to Global talker discrimination ($r_s = 0.53$, $p = 0.044$), but not to Mixed-gender or Same-gender talker discrimination. Thus, as was found for age, neurocognitive abilities were more consistently related to Global talker discrimination and Mixed-gender talker discrimination abilities.

4.3. Multiple-talker sentence recognition

Finally, correlational analyses were carried out between the three talker discrimination metrics and multiple-talker sentence recognition accuracy on PRESTO sentences. Results are also displayed in Table 4. Same-gender discrimination was significantly related to PRESTO sentence recognition accuracy ($r_s = 0.66$, $p = 0.035$), shown in Fig. 5. Global and Mixed-gender talker discrimination abilities were not significantly related to PRESTO sentence recognition accuracy.

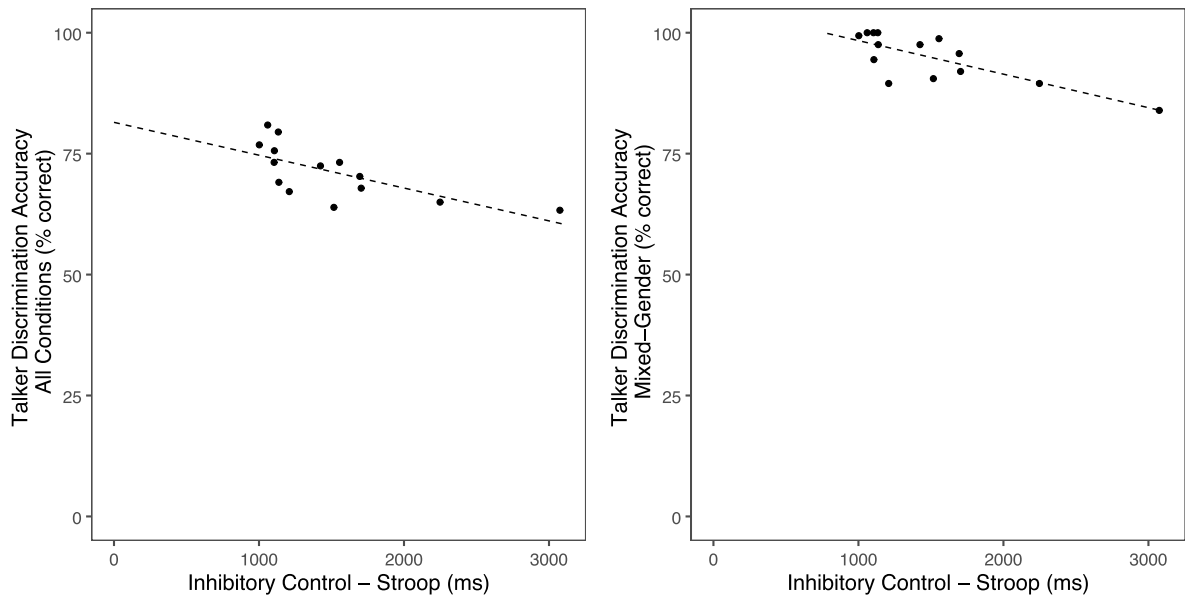


Fig. 4. Scatterplots showing the relation between Global talker discrimination ability (% correct) and inhibitory control (Stroop; ms) (left) and Mixed-gender talker discrimination ability (% correct) and inhibitory control (Stroop; ms) (right).

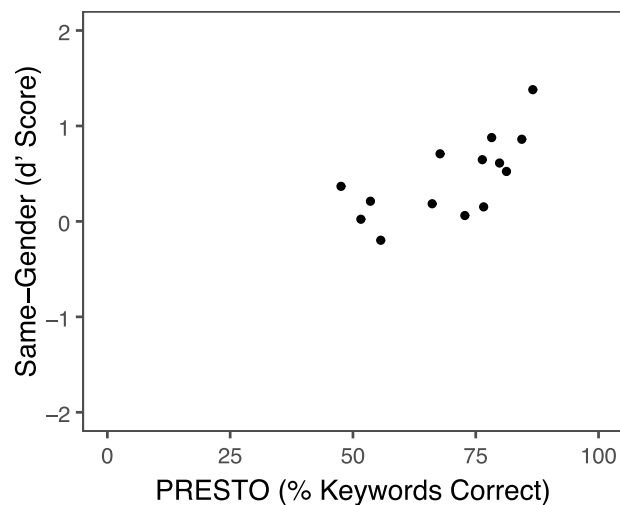


Fig. 5. Scatterplot showing the relation between Same-gender talker discrimination ability (d' score) and multiple-talker sentence recognition scores on PRESTO (% keywords correct).

5. Discussion

The current study investigated talker discrimination ability in experienced, high-performing adult CI users. The first goal of the study was to characterize talker discrimination abilities in this patient population. We sought to replicate previous findings in adult CI users, but specifically in a group of higher-performing adult CI users. Consistent with previous findings and our initial hypothesis, the CI users in the current study demonstrated relatively poor discrimination of two talkers of the same gender (i.e., female-female, male-male) but relatively good discrimination of two talkers of different genders (i.e., male-female). The relatively high-performing CI users in the current study were around chance performance for same-gender talker pairs, comparable to previous studies in CI users and further suggesting that same-gender talker discrimination is relatively challenging for all CI users. Discrimination was relatively better for mixed-gender talker pairs, also consistent with previous findings (McDonald et al., 2003; Osberger et al., 1991; Tamati et al., 2020b). Importantly, participants also displayed a wide range of performance in both same-gender and mixed-gender talker discrimination, similar to previous studies exploring talker (Hay-McCutcheon et al., 2018), gender (Massida et al., 2013), and accent discrimination (Tamati et al., 2021a). Thus, the high-performing CI users in the current study showed talker discrimination abilities

that were widely consistent with previous findings.

The second goal of the current study was to investigate potential sources of individual differences in talker discrimination ability. We first examined the association between global, same-gender, and mixed-gender talker discrimination and age. Given prior studies demonstrating an inverse relation between age and speech recognition ability in CI users (Beyea et al., 2016; Mahmoud & Ruckenstein, 2014; Williamson et al., 2009) as well as age and talker perception in NH adults (Pichora-Fuller, 2003; Sommers, 1997), we hypothesized that a similar relationship would be found with age and talker discrimination ability in the CI users. Indeed, we noted a negative association between age and talker discrimination for the global and mixed-gender scores. Thus, individuals with older age demonstrated poorer talker discrimination ability, with the largest effect for mixed-gender talker discrimination.

The effect of aging on CI speech recognition has been shown to be a function of age-related deterioration in both auditory sensitivity and neurocognitive skills (Moberly et al., 2018b). Therefore, we examined the relation between auditory sensitivity and talker discrimination in the experienced, high-performing CI users. Although previous studies suggest age-related declines in auditory sensitivity may contribute to poorer talker discrimination (Souza et al., 2011; Vongpaisal & Pichora-Fuller, 2007), in the current study, spectro-temporal processing, assessed using the SMRT, was not significantly correlated with talker discrimination ability. Same-gender talker discrimination requires good perception of fine-grained talker-specific voice cues, including formant frequency information related to vocal tract information, which is largely dependent upon spectral resolution (Gaudrain & Başkent, 2015, 2018). However, cues for mixed-gender discrimination should be relatively more disparate, and therefore more accessible to many CI users (Gaudrain & Başkent, 2018). As such, bottom-up auditory sensitivity would be expected to be relatively more important for same-gender talker discrimination than for mixed-gender talker discrimination, or other nonlinguistic judgements such as gender discrimination (Fuller et al., 2014). However, the results of the current study suggest that same-gender talker discrimination is not strongly related to spectro-temporal processing skills, at least as measured by the SMRT task. CI users with good same-gender talker discrimination ability may have been relying more heavily on talker-specific cues that are better conveyed by the device, such as articulation rate and speaking style (Tamati et al., 2019). Yet, it should also be noted that due to aliasing at high ripple densities, the SMRT task may not be truly reflective of spectro-temporal processing in high-performing CI users (Winn & O'Brien, 2022). Thus, while spectro-temporal processing was not significantly correlated with talker discrimination ability in the current study, it is possible that specific auditory tests of voice cue perception may demonstrate a stronger relation. Testing a wider range of auditory processing skills as well as identifying specific cues used in talker discrimination would further elucidate the relation between bottom-up auditory skills and talker discrimination ability.

We also explored the contribution of neurocognitive skills on talker discrimination ability. Similar to prior studies examining the effect of age on performance in hearing tasks such as speech perception (Beyea et al., 2016; Moberly et al., 2018b), we expected that age-associated declines in neurocognitive skills would also impact talker discrimination ability in adult CI users. In the current study, inhibitory control, speed of lexical access, and nonverbal reasoning were related to global talker discrimination ability; inhibitory control was also specifically related to mixed-gender talker discrimination ability. Inhibitory control was most strongly related to talker discrimination ability; individual CI users with weaker inhibitory control demonstrated poorer talker discrimination ability, specifically global and mixed-gender discrimination ability. Inhibitory control has previously been shown to be related to sentence recognition in noise (Beyea et al., 2016; Moberly, Houston, & Castellanos, 2016). Additionally, inhibitory control has been shown to be associated with faster adaptation to unfamiliar accents (Banks et al., 2015), suggesting that it may contribute to the processing of linguistic and nonlinguistic talker information in speech. Similarly, in the current study, inhibitory control may have enabled participants to ignore other irrelevant information (e.g., variable linguistic content) when making talker discrimination judgements.

CI users with stronger speed of lexical access and stronger nonverbal reasoning also demonstrated more accurate overall talker discrimination. Speed of lexical access (Moberly et al., 2018a; Tamati et al., 2021b) and nonverbal reasoning (Holden et al., 2013; Knutson et al., 1991; Mattingly et al., 2018; Moberly et al., 2018a) have been found to be related to sentence recognition abilities in adult CI users. More efficient lexical processing may facilitate speech recognition in adult CI users since greater cognitive resources are available for additional processing of speech in context or resolving additional ambiguities (Mishra et al., 2013, 2014; Rönnberg et al., 2013). Nonverbal reasoning, reflecting the ability to solve novel reasoning tasks with new information without use of prior knowledge, may underlie CI users' ability to extract meaning from highly degraded speech signals (Mattingly et al., 2018; Moberly et al., 2019). Further, nonverbal reasoning may contribute to the speed or efficiency at which the degraded signal is processed, since it has been found to depend at least partially on information processing speed in adult CI users (Moberly et al., 2019). Although the focus of the current study was on talker information, similarly more efficient processing in adult CI users may free up additional resources for the perceptual encoding and retention of talker-specific details in degraded speech, resulting in improved talker discrimination abilities. Thus, taken together, the findings of the current study and previous studies suggest that both speed of lexical access and nonverbal reasoning may contribute to the efficient processing of both linguistic and indexical information in spectro-temporally degraded speech.

Individual differences in neurocognitive skills may have also influenced listeners' perceptual strategies in the talker discrimination task, in particular with respect to their ability to make use of available, but degraded, voice cue information. Accuracy for mixed-gender talker discrimination was high, suggesting that the high-performing CI users in the current study had access to relevant voice cue information to discriminate between talkers of different genders. Yet, although they are able to achieve good mixed-gender discrimination, it is possible that not all CI users were relying on the same cues and/or showing similar weighting of these cues. For example, in contrast with NH listeners who utilize both F0 and vocal tract length information in gender categorization, previous research has shown that CI users rely almost exclusively on F0 with listeners reporting minimal perceptual weighting to vocal tract length (Fuller et al., 2014). Thus, CI users achieve gender categorization with abnormal weighting of voice cues. However, although not the focus of their study, Fuller et al. (2014) reported individual differences in cue weighting for gender categorization among CI

users. In the current study, it is possible that some CI users adopt different perceptual strategies (and perceptual weighting) of talker voice and/or speech information to discriminate mixed-gender talkers, with neurocognitive functioning moderating a given listener's ability to do so. Although future research is required to more fully understand how neurocognitive skills – and specifically inhibitory control – affect talker discrimination, the results from the present study suggest that age-related declines in neurocognitive functioning may impair talker discrimination.

Findings from the current study suggest that different underlying mechanisms may be involved in same-gender and mixed-gender talker discrimination. For mixed-gender pairs, CI users show relatively high accuracy at using disparate cues for talker discrimination. Thus, when talker cues are available, albeit degraded, for mixed-gender pairs, differing neurocognitive abilities, possibly related to aging, are associated with how well individual CI users can utilize the available cues to perform the task. In contrast, cues for same-gender talker discrimination may not be sufficiently available to CI users to allow for neurocognitive functions to play a role. Indeed, overall performance in the same-gender condition was near floor, potentially constrained by limitations in CI hearing. Although the source of this poor performance cannot be determined in this study, such poor performance would also restrict the ability to observe a meaningful relation between same-gender talker discrimination and neurocognitive abilities. In other words, the signal quality is so degraded that cognitive compensatory mechanisms cannot be effectively used in same-gender talker discrimination.

The final goal of the current study was to examine the relation between talker discrimination ability and speech recognition in challenging listening conditions. In the current study, same-gender talker discrimination was associated with PRESTO sentence recognition scores, suggesting that access to subtle talker-specific cues is crucial for both same-gender talker discrimination as well as rapid talker adaptation on a multiple-talker sentence recognition task. This finding is consistent with previous studies demonstrating impaired talker and accent adaptation in CI users and NH listeners under CI simulation (Kapolowicz et al., 2018, 2020). Therefore, CI users who are better able to accurately discriminate between same-gender talkers using fine-grained talker information likely display better overall signal quality, promoting overall stronger speech recognition abilities, compared to CI users who are less accurate at discriminating between same-gender talkers. In contrast to same-gender talker discrimination, CI users in the current study performed at high levels for mixed-gender talker discrimination, and all had access to gender-related cues. Similarly, Winn and Moore (2020) found that CI users, as a group, demonstrated the ability to accommodate gender-related phonetic differences in speech (Winn & Moore, 2020). Thus, individual variability in mixed-gender talker discrimination may not specifically relate to the difficulties associated with speech recognition in challenging listening conditions. However, it is possible that relations between mixed-gender talker discrimination and speech recognition would arise for relatively poorer-performers, who may display even poorer signal quality affecting the perception of gender-specific cues.

Some limitations of the study should be addressed. The findings in the present study would be further strengthened by a larger sample size to explore these underlying mechanisms and how they may relate to any age-related neurocognitive or auditory deficits. It would also be helpful to include additional neurocognitive assessments to provide converging measures of each neurocognitive domain. Additionally, the study included both bilateral and unilateral CI users. Although previous studies have suggested a benefit to electro-acoustic-stimulation in gender discrimination (Başkent et al., 2018) we were unable to explore this potential contributing factor due to the small sample size. Future studies should aim to include larger and more homogeneous sample sizes, and use a wider range of neurocognitive and auditory tasks to fully explore the potential underlying factors contributing to poor talker discrimination in adult CI users.

6. Conclusion

Listening in challenging conditions remains a significant problem for CI users, with deficits in talker discrimination potentially contributing to this difficulty. Here, high-performing CI users showed poor same-gender talker discrimination, but relatively good mixed-gender talker discrimination. Age and neurocognitive skills were related to talker discrimination ability, specifically for mixed-gender talker pairs, for which cues are relatively more disparate. Thus, older age and poorer neurocognitive skills may contribute to poorer talker discrimination ability observed in some post-lingually deafened, adult CI users. While neurocognitive skills were not associated with same-gender talker discrimination, performance on this task was predictive of PRESTO sentence recognition, suggesting that availability of subtle talker-specific cues may be important for speech recognition and adaptation in challenging listening conditions.

CRediT authorship contribution statement

Michael M. Li: Formal analysis, Writing – original draft, Writing – review & editing, Visualization. **Aaron C. Moberly:** Conceptualization, Formal analysis, Writing – original draft, Writing – review & editing, Visualization, Supervision, Funding acquisition. **Terrin N. Tamati:** Conceptualization, Methodology, Software, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Visualization, Supervision, Funding acquisition.

Declaration of Competing Interest

A.C.M. received grant funding support from Cochlear Americas for an unrelated investigator-initiated research study. A.C.M. serves as a paid consultant for Cochlear Americas and Advanced Bionics and is CMO and on Board of Directors for Otologic Technologies.

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