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Talker Adaptation and Lexical Difficulty Impact Word Recognition in Adults with Cochlear Implants

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Keywords
Cochlear implants · Word recognition · Individual differences · Talker adaptation

Abstract

Introduction: Talker-specific adaptation facilitates speech recognition in normal-hearing listeners. This study examined talker adaptation in adult cochlear implant (CI) users. Three hypotheses were tested: (1) high-performing adult CI users show improved word recognition following exposure to a talker ("talker adaptation"), particularly for lexically hard words, (2) individual performance is determined by auditory sensitivity and neurocognitive skills, and (3) individual performance relates to real-world functioning. ***Methods:*** Fifteen high-performing, post-lingually deaf adult CI users completed a word recognition task consisting of 6 single-talker blocks (3 female/3 male native English speakers); words were lexically "easy" and "hard." Recognition accuracy was assessed "early" and "late" (first vs. last 10 trials); adaptation was assessed as the difference between late and early accuracy. Participants also completed measures of spectral-temporal processing and neurocognitive skills, as well as real-world measures of multiple-talker sentence recognition and quality of life (QoL). ***Results:*** CI users showed limited talker adaptation overall, but performance improved for lexically hard words. Stronger spectral-temporal processing and neurocognitive skills were weakly to moderately associated with more accurate word recognition and greater talker adaptation for hard words. Finally, word recognition accuracy for hard words was moderately related to multiple-talker sentence recognition and QoL. ***Conclusion:*** Findings demonstrate a limited talker adaptation benefit for recognition of hard words in adult CI users. Both auditory sensitivity and neurocognitive skills contribute to performance, suggesting additional benefit from adaptation for individuals with stronger skills. Finally, processing differences related to talker adaptation and lexical difficulty may be relevant to real-world functioning.

Introduction

Cochlear implants (CIs) are successful in restoring the sense of hearing to adults with severe-to-profound hearing loss (HL). Adult CI users are generally able to achieve good recognition accuracy for idealized speech – carefully articulated, linguistically simple materials produced by a single talker with no discernible accent – commonly used in clinical measures, such as the consonant-nucleus-consonant (CNC) word test [Peterson and Lehiste, 1962].

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However, the adverse listening conditions encountered in daily life may present significant challenges to successful speech understanding.

One potential source of difficulty for adult CI users is the immense amount of talker variability experienced in real-world listening conditions [Pisoni, 1997]. Compared to idealized speech, understanding speech produced by multiple talkers or dealing with variability from regional or foreign accents can be challenging (e.g., [Peters, 1955; Mullennix et al., 1989; Clopper and Bradlow, 2008; Bent and Holt, 2013; Tamati et al., 2013]). In normal-hearing (NH) listeners, experience with a talker facilitates speech recognition ("talker adaptation") [Nygaard et al., 1994; Nygaard and Pisoni, 1998; Johnsrude et al., 2013; Souza et al., 2013], as a result of their ability to perceive, encode, and retain in memory detailed talker-specific information. In particular, learning talker-specific voice and speech characteristics improves the recognition of lexically hard words by enabling listeners to tune into relevant phonetic details [Bradlow and Pisoni, 1999]. Lexically hard words – compared to easy words – are less frequent with many phonemically similar neighbors and are more difficult to recognize [Howes, 1957; Savin, 1963; Luce, 1998], requiring fine-grained phonetic discrimination. Further, recent evidence suggests that rapid adaptation and learning ability may contribute to individual differences in speech recognition accuracy in challenging listening conditions [Rotman et al., 2020]. *Talker adaptation ability* may therefore also be relevant to real-world speech communication success in adult CI users.

Real-world speech communication may pose significant difficulties for adult CI users, since they rely on signals that are degraded in acoustic-phonetic detail, due to the limitations of the electrode-nerve interface and the broad electrical stimulation of the auditory nerve (for a review, see Başkent et al. [2016b]). Previous research has shown that adult CI users have difficulty understanding speech produced by multiple talkers (e.g., [Sommers et al., 1997; Fu et al., 2002; Gifford et al., 2008]) and foreign-accented speech [Ji et al., 2014; Kapolowicz et al., 2020]. Additionally, lexically hard words may be more challenging when produced by multiple talkers [Sommers et al., 1997; Sommers and Barcroft, 2006]. As such, these talker and linguistic challenges may hinder CI users' everyday communication and impact the overall quality of life (QoL). Yet, little is still known about how differences in the extent to which CI users can compensate for these challenges through talker adaptation contribute to real-world communication success.

Limitations in the perception of talker details may limit talker adaptation in adult CI users. CI users demonstrate relatively poor discrimination and identification of talkers' voices, vocal emotion, as well as regional and foreign accents [Cleary and Pisoni, 2002; McDonald et al., 2003; Cleary et al., 2005; Vongphoe and Zeng, 2005; Xin et al., 2007; Massida et al., 2011; Jiam et al., 2017; Hay-McCutcheon et al., 2018; Tamati et al., 2021]. Specifically examining adaptation, Kapolowicz et al. [2020] found that CI users displayed no improvement in sentence recognition accuracy with exposure to 40 sentences produced by either a single or multiple nonnative talkers. While their results suggest little to no rapid adaptation to foreign accented speech in adult CI users, a great deal of variability was observed across CI users. Some CI users were able to benefit from exposure to nonnative speech and reached accuracy levels similar to NH listeners. Similarly, studies using noise-vocoding to simulate CI hearing have 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 the perception of talker details [Kapolowicz et al., 2018; Tamati et al., 2020b].

More broadly, variability in basic auditory sensitivity contributes to speech recognition outcomes in adult CI users [Henry et al., 2005; Won et al., 2007, 2010]. Spectral-temporal resolution varies among individual implant users [Won et al., 2007]. Individual CI users with good spectral-temporal processing may be better able to utilize acoustic-phonetic details [Croghan et al., 2017]. Taken together, the previous studies suggest that talker adaptation processes may be abnormal in CI users, at least in part due to limitations in CI hearing. Further, individual CI users may vary substantially in talker adaptation ability, although the relation to signal quality is still unknown.

CI users' ability to compensate for poor signal quality may also contribute to talker adaptation. Neurocognitive processes and language knowledge are used to compensate for degraded sensory input (e.g., [Başkent et al., 2016a]). Yet, the processing load associated with processing degraded speech may tax limited cognitive processes, leaving fewer resources to dedicate for other tasks [Rabbit, 1968, 1991; McCoy et al., 2005], such as encoding talker-specific details that facilitate speech recognition. Several neurocognitive abilities have been found to be related to speech recognition outcomes in hearing-impaired adults (e.g., [Arehart et al., 2013]) and adult CI users (e.g., [Heydebrand et al., 2007; Holden et al., 2013]). Some specific neurocognitive skills, such as working memory capacity, are consistently strongly related to speech perception and potentially more so than general cognitive abilities, such

Table 1. Participant demographics and hearing history

Subject 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	F	57	44	19	Left	Cochlear	No	74	120
3	M	58	50	29	Bilateral	Cochlear	N/A	88	120
4	M	63	57	2	Bilateral	Cochlear	N/A	94	120
5	M	81	72	16	Bilateral	Cochlear	N/A	80	120
6	M	87	76	26	Right	Cochlear	Yes	72	68.75
7	M	70	60	46	Left	Cochlear	No	92	80
8	F	39	31	15	Left	Cochlear	Yes	86	116.25
9	M	63	55	3	Right	Cochlear	Yes	76	111.25
10	M	56	48	50	Bilateral	Cochlear	N/A	70	120
11	M	85	82	32	Bilateral	Cochlear	N/A	70	78
12	F	70	66	Unknown	Bilateral	Cochlear	N/A	86	120
13	M	69	68	26	Left	Cochlear	Yes	82	83
14	M	63	60	Unknown	Left	Cochlear	Yes	66	112.5
15	M	75	73	33	Right	Cochlear	Yes	88	66

CNC, consonant-nucleus-consonant; PTA, unaided pure-tone average across 0.5, 1, 2, and 4 kHz.

as nonverbal intelligence (for a review, see Akeroyd [2008]). Specifically in adult CI users, speech recognition outcomes have been found to be related to working memory capacity, inhibitory control, and nonverbal reasoning (e.g., [Tao et al., 2014; Moberly et al., 2016; Mattingly et al., 2018; O'Neill et al., 2019]). Still, little is known about the neurocognitive factors underlying talker adaptation in adult CI users.

The primary goal of the current study was to examine the effects of talker adaptation and lexical difficulty on word recognition in adult CI users. Word recognition in adult CI users was examined both during early trials (i.e., before adaptation) and later trials (i.e., following adaptation) in single-talker blocks. Both lexically hard and easy words were selected given that the previous findings suggest that adaptation may be more beneficial to the recognition of hard words. Additionally, we investigated individual differences in early and late word recognition as well as talker adaptation ability, auditory and neurocognitive sources of individual differences, and their relation to real-world communication success through assessing multiple-talker sentence recognition and QoL. Specifically, we hypothesized that (1) experienced adult CI users will show talker adaptation with short-term exposure to a talker, in particular for linguistically challenging words; (2) individual differences in word recognition and adaptation will depend on auditory sensitivity and neurocognitive skills; and (3) individual differences will relate to real-world functioning outcomes in adult CI users.

Materials and Methods

Participants

Fifteen post-lingually deafened CI users participated, all with >1 year of CI experience. Participants included 4 females and 11 males, ages 39–87 years ($M = 66.9$ years, SD = 12.4). All participants were native English speakers, with at least a high school diploma or equivalent, and demonstrated cognitive scores above passing criteria (≥24) on a written version of the Mini-Mental State Examination (MMSE; [Folstein et al., 1975]).

All participants were relatively high performers with isolated word recognition scores of 66–94% ($M = 80.3\%$, SD = 8.7) on the CNC word test [Peterson and Lehiste, 1962]. During testing, participants wore typical hearing prostheses including both CIs for bilateral CI users ($n = 7$), hearing aids (HAs) for bimodal CI users ($n = 6$), or a single CI for unilateral CI users without HAs ($n = 2$). Additional demographics are provided in Table 1. All participants provided informed written consent prior to participation and received USD 15 per hour for their time. Institutional Review Board (IRB) approval was obtained.

Measures and Procedures

Word Recognition Task

A word recognition task assessed participants' isolated word recognition and talker adaptation abilities in quiet. To ensure that any improvement was not related to learning the task and/or a specific talker's voice, adaptation was tested across multiple talkers. In particular, the task included 6 separate blocks, each with a different talker. The 6 talkers included in the task were 3 female and 3 male native speakers of American English, selected from the PB/MRT Word Multi-Talker Speech Database from Indiana University, based on the Modified Rhyme Test (MRT, [House et al., 1965]). Each block included forty isolated words produced by a single talker; 20 were lexically easy, and 20 were lexically hard words, based on frequency and density characteristics of the PB/MRT corpus

[Balota et al., 2007]. Block/talker orders were randomly assigned to each participant. All words were unique and were not repeated within or across blocks.

On each trial, participants heard a single word, which was not repeated. All words were presented randomly at 70 dB SPL via a loudspeaker, approximately 1 m from the participant at 0° azimuth. Participants repeated the words aloud to the best of their ability. Oral responses were scored offline for words correct. For analysis, the 40 trials were further broken down into subblocks based on presentation order. The first 10 trials were considered the early subblock (Q1), and the last 10 trials were considered the late subblock (Q4). Talker adaptation (TA) was defined as the difference in accuracy between Q4 and Q1 (TA = Q4–Q1). The 3 metrics – Q1, Q4, and TA – were analyzed by lexical difficulty.

Auditory Spectral-Temporal Processing

Spectral-temporal processing was assessed using the spectral-temporally modulated ripple test (SMRT) with details in [Aronoff and Landsberger, 2013]. SMRT stimuli were 202 pure-tone frequency components, modulated by a sine wave at different ripple densities. The task consisted of a three-interval, 2-alternative forced-choice task in which two of the intervals contained a reference signal with 20 ripples per octave, and one contained the target signal. Participants were asked to determine the reference from the target stimuli. The test was completed after 6 runs of 10 reversals. A ripple detection threshold was calculated based on the last 6 reversals; a higher threshold represented better spectral-temporal processing.

Nonauditory Neurocognitive Measures

Working memory capacity was assessed using a visual digit span task [Wechlsler, 2004]. Participants reproduced visual lists of (2–7) ordered digits by tapping the digits in a 3 × 3 matrix on the computer touchscreen. Total correct items (sequences) were used for analysis.

A computerized Stroop test (http://millisecond.com), based on Stroop [1935], assessed inhibitory control. Participants pressed a key on a keyboard corresponding to the font color of a color word (e.g., red) or a colored rectangle presented on the computer screen. Response times for both congruent (matching color word and font color) and incongruent word trials (mismatching color word and font color), as well as a control condition in which a colored rectangle was presented, were collected. The difference in response times from the incongruent and congruent trials was used as a measure of inhibitory control. Note that stronger inhibitory control is reflected in lower scores.

Raven's Progressive Matrices test was used to obtain a global measure of nonverbal reasoning [Raven, 2000]. Participants completed incomplete visual patterns on a touchscreen monitor by selecting the best option from a closed set of alternatives. Scores were the number of correct items in 10 min.

Real-World Functioning

The Perceptually Robust English Sentence Test Open-set (PRESTO) sentence recognition test [Gilbert et al., 2013] was used to assess multiple-talker sentence recognition. Participants repeated 32 PRESTO sentences (2 practice + 30 test), originally selected from the TIMIT (Texas Instruments/Massachusetts Institute of Technology) speech corpus [Garofolo et al., 1993]. PRESTO maximizes talker variability by including sentences produced by multiple male and female talkers with different regional accents. Scores represent percent keywords correct across the 30 test sentences.

The Nijmegen Cochlear Implant Questionnaire (NCIQ; [Hinderink et al., 2000]) was used to assess QoL. The NCIQ is a CI-specific QoL measure that includes an overall score based on 3 domains (and 6 subdomains): physical functioning (basic sound perception, advanced sound perception, and speech production); psychological functioning (self-esteem); and social functioning (activity limitations and social interactions). The overall QoL score (max 300) was used as a broad measure of real-world functioning.

Data Analysis

Word Recognition and Talker Adaptation

The effect of talker adaptation and its potential interactions with lexical difficulty on word recognition were first examined in a repeated-measures ANOVA on word recognition accuracy with lexical difficulty (easy and hard), and subblock (Q1 and Q4) as within-subject factors. To further examine talker adaptation, TA scores for easy and hard words (and overall) were subjected to 1-sample t tests.

Individual Differences

To examine the relations between word recognition and spectral-temporal processing and neurocognitive abilities, Pearson correlations were calculated between the word recognition metrics (Q1, Q4, and TA) and scores on the SMRT task as well as nonauditory neurocognitive measures.

Word Recognition and Real-World Functioning

Finally, Pearson correlations were carried out between the word recognition metrics (Q1, Q4, and TA) and PRESTO and QoL scores to determine the relation between word recognition and real-world functioning in adult CI users.

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 correction was used for multiple comparisons; corrected p are reported.

Results

Word Recognition and Talker Adaptation

Mean word recognition accuracy scores by lexical difficulty (easy and hard) and subblock (Q1 and Q4) are shown in Figure 1 and mean TA (difference) scores by lexical difficulty in Figure 2. A summary of all performance metrics is provided in Table 2. The 2-way repeated measures ANOVA revealed a significant main effect of lexical difficulty (easy and hard) (F [1, 14] = 30.81, $p <$ 0.001, $\eta_p^2 = 0.69$). A post hoc paired t test confirmed that easy words were more accurately recognized than hard words (t [14] = 7.4, $p < 0.001$, Cohen's $d = 1.03$). The main effect of subblock (Q1 and Q4) (F [1, 14] = 1.09, $p = 0.315$, $\eta_p^2 = 0.07$) and the lexical difficulty × subblock interaction (F [1, 14] = 3.35, $p = 0.09$, $\eta_p^2 = 0.19$) did not reach significance. However, 1-sample t tests on TA (difference)

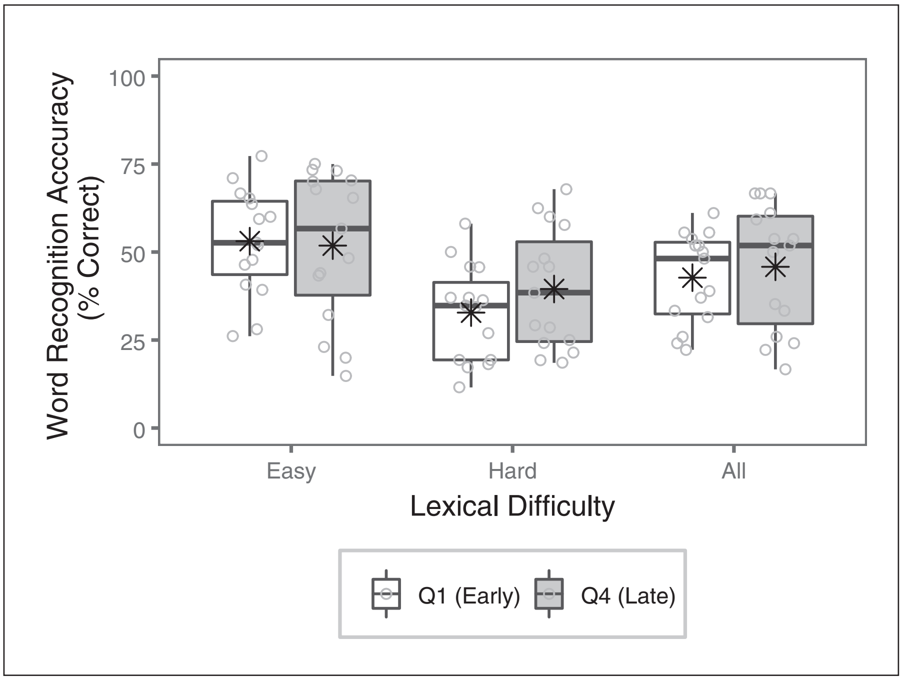

Fig. 1. Box plot showing the mean word recognition accuracy (% correct) by lexical difficulty (easy, hard, and all) and subblock (Q1 and Q4). Early trials are represented by open boxes, and late trials are represented by filled gray boxes. The boxes extend from the lower to the upper quartile (IQR), the solid midline indicates the median, and the star indicates the mean. The whiskers indicate the highest and lowest values no >1.5 times the IQR, and the plus signs indicate outliers, which are defined as data points >1.5 times the IQR. Individual data points are plotted in gray on the boxplots. IQR, interquartile range.

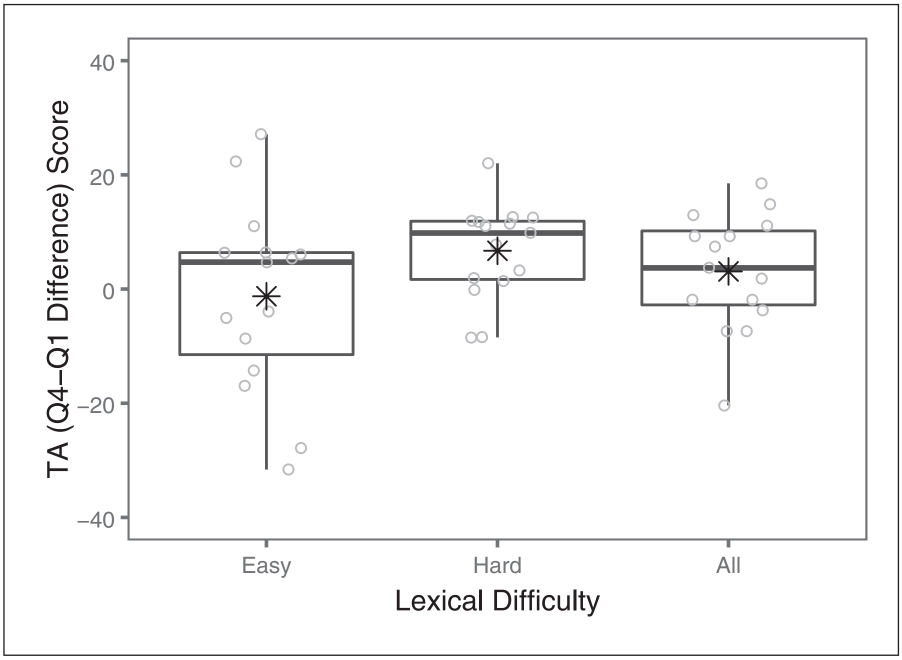

Fig. 2. Box plot showing the mean TA difference score (Q4–Q1) in points by lexical difficulty (easy, hard, and all). The boxes extend from the lower to the upper quartile (IQR), the solid midline indicates the median, and the star indicates the mean. The whiskers indicate the highest and lowest values no >1.5 times the IQR, and the plus signs indicate outliers, which are defined as data points >1.5 times the IQR. Individual data points are plotted in gray on the boxplots. TA, talker adaptation; IQR, interquartile range.

scores demonstrated that TA scores for hard words were significantly different than 0 (t [14] = 3.11, p = 0.008, Cohen's d = 0.80). The TA scores for all words (t [14] = 1.15, p = 0.268, Cohen's d = 0.30) and for easy words (t [14] = −0.29, p = 0.774, Cohen's d = −0.08) were not significantly different than 0.

Individual Differences

As shown in Figures 1 and 2 and summarized in Table 2, CI users varied substantially in both Q1 and Q4 word recognition accuracy and adaptation. Examining TA scores, 8 out of 15 participants showed a positive performance gain for easy words, and 12 out of 15 participants showed

Table 2. Mean (SD) and range for performance metrics

Task	Lexical difficulty	M, %	SD	Range
Word recognition				
Q1	Easy	53.1	15.1	26.1–77.2
	Hard	32.8	13.7	11.5–58.1
	All	42.7	13.0	22.2–61.1
Q4	Easy	51.8	21.3	14.8–75.0
	Hard	39.5	17.1	18.5–67.9
	All	45.8	17.8	16.7–66.7
TA	Easy	–1.3	16.7	–31.6 to 27.1
	Hard	6.7	8.4	–8.5 to 22.0
	All	3.1	10.4	–20.4 to 18.5
Spectral-temporal Processing (SMRT)		2.7	1.4	0.7–5.1
Working memory (digit span)		45.9	19.2	14.0–83.0
Inhibitory control (Stroop)		242.9	228.8	–50.9 to 841.0
Nonverbal reasoning (Raven's)		12.3	5.3	2.0–20.0
Multiple-talker sentence recognition (PRESTO)		67.4	15.9	32.3–86.6
QoL (NCIQ)		191.7	32.3	122.2–237.5

SMRT, spectral-temporally modulated ripple test; PRESTO, Perceptually Robust English Sentence Test Open-set; QoL, quality of life; NCIQ, Nijmegen Cochlear Implant Questionnaire; TA, talker adaptation.

a positive performance gain for hard words (for all words, 9 out of 15). Table 3 shows a summary of the results of Pearson correlations between the 3 word recognition metrics (Q1, Q4, and TA) for both easy and hard words and individual auditory sensitivity and nonauditory neurocognitive abilities. Summarizing the strength and significance of the observed relations, Q1 scores for both easy and hard words were weakly to moderately related to spectral-temporal processing (SMRT), but only Q1 scores for hard words reached significance. Q1 scores for hard words were also weakly but not significantly related to nonverbal reasoning (Raven's matrices). Q4 scores for easy words were moderately but not significantly related to spectral-temporal processing (SMRT). Q4 scores for hard words were weakly to moderately and significantly related to spectral-temporal processing (SMRT) and inhibitory control (Stroop), and nonverbal reasoning (Raven's matrices). Finally, TA-easy (difference) scores showed only negligible relations to individual factors; TA scores for hard words showed weak to moderate, but not significant with correction, relations to spectral-temporal processing (SMRT), inhibitory control (Stroop), and nonverbal reasoning (Raven's matrices).

Word Recognition and Real-World Functioning

Table 3 also shows the results of Pearson correlations between the word recognition metrics (Q1, Q4, and TA) for easy and hard words and multiple-talker sentence recognition (PRESTO) and QoL (NCIQ). PRESTO scores were moderately and significantly related to Q1 and Q4 scores for hard words and moderately but not significantly related to Q1 and Q4 scores for easy words. NCIQ scores were moderately and significantly related to Q1 and Q4 scores for hard words and also weakly but not significantly related to Q1 for easy and hard words. TA scores were not related to either PRESTO or NCIQ scores.

Discussion

The current study examined talker adaptation in the recognition of lexically easy and hard words in high-performing adult CI users. Contrary to our initial prediction, CI users did not show a substantial improvement in performance from Q1 to Q4, as demonstrated by the lack of main effect of subblock on word recognition accuracy. While NH listeners consistently demonstrate a benefit from talker adaptation [Nygaard et al., 1994; Nygaard and Pisoni, 1998; Johnsrude et al., 2013; Souza et al., 2013], this group of CI users did not show substantial evidence of talker adaptation. Consistent with the previous research demonstrating impaired accent adaptation in CI users [Kapolowicz et al., 2020], these results further suggest that adult CI users experience limitations in talker adaptation.

Nonetheless, analyses of difference scores across lexical difficulty provide some evidence for adaptation.

Table 3. Pearson correlations between word recognition metrics and scores from measures of spectral-temporal processing, neurocognitive skills, multiple-talker sentence recognition, and QoL

Word recognition metric	Lexical difficulty	Spectral-temporal processing (SMRT)	Working memory (digit span)	Inhibitory control (Stroop)	Nonverbal reasoning (Raven's)	MT sentence recognition (PRESTO)	QoL (NCIQ)
Q1	Easy	**0.50**	−0.15	−0.22	−0.09	**0.52**	*0.40*
		0.084	0.350	0.317	0.372	0.084	0.144
	Hard	**0.55**	0.19	−0.27	*0.32*	**0.68**	**0.59**
		0.034	0.246	0.197	0.180	**0.018**	**0.030**
Q4	Easy	**0.54**	−0.14	−0.05	0.14	**0.51**	*0.41*
		0.081	0.371	0.430	0.371	0.081	0.126
	Hard	**0.67**	0.17	**−0.50**	*0.47*	**0.68**	**0.57**
		0.009	0.269	**0.044**	**0.048**	**0.009**	**0.028**
TA	Easy	0.23	−0.04	0.14	0.26	0.17	0.17
		0.371	0.444	0.371	0.371	0.371	0.371
	Hard	*0.48*	0.04	**−0.58**	*0.42*	0.28	0.19
		0.108	0.448	0.072	0.116	0.236	0.295

MT, Multiple-talker; SMRT, spectral-temporally modulated ripple test; PRESTO, Perceptually Robust English Sentence Test Open-set; QoL, quality of life; NCIQ, Nijmegen Cochlear Implant Questionnaire; TA, talker adaptation.

Bolded *p* values are significant after FDR correction. Italicized *r* values indicate weak correlations ($0.3 < r < 0.5$); bolded *r* values indicate moderate correlations ($0.5 < r < 0.7$).

Specifically, CI users' difference scores were significantly >0 for lexically hard words. Lexically hard words are more challenging to recognize, due to being less frequent and sharing phonemic similarity with several other words. Talker adaptation has been proposed to more strongly benefit recognition of hard words [Bradlow and Pisoni, 1999] because it allows the listeners to tune into linguistically relevant, talker-specific details, while ignoring nonlinguistic details. Thus, the CI users appear to have benefited from talker adaptation in the perception of fine phonetic details required for the recognition of hard words. Here, CI users had only short exposure to unfamiliar talkers (total 40 words), and adaptation was assessed for isolated words, which may have offered limited information for learning for adult CI users. Future studies should also examine to what extent talker adaptation in CI users may depend on the duration of the exposure or on the content of the utterances (e.g., words vs. sentences).

To better understand talker adaptation abilities, we also examined individual differences in performance on the word recognition task. Although the CI users in the current study were all relatively high performing, they showed vast individual differences in early (Q1) and late (Q4) word recognition accuracy and in talker adaptation benefits (TA). Interestingly, Q1 scores (for both easy and hard words) – representing baseline recognition before adaptation – were weakly to moderately related to spectral-temporal processing, measured by the SMRT task. In contrast, Q4 scores (specifically for hard words) – representing recognition after adaptation has occurred and peak performance is reached – were moderately related to spectral-temporal processing (SMRT), inhibitory control (Stroop), and nonverbal reasoning (Raven's matrices). Finally, amount of adaptation for hard words was weakly to moderately (but not significantly) related to spectral-temporal processing and inhibitory control. These findings suggest that auditory sensitively and neurocognitive skills impact the amount of talker adaptation CI users experience (TA scores) and, in particular, in the peak level achieved with adaptation (Q4 scores). More broadly, these findings are also consistent with the previous findings in NH listeners demonstrating a role for cognitive-linguistic processes and, specifically, for attentional and inhibitory processes in adaptation and learning [Banks et al., 2015]. These results suggest that CI users with stronger auditory and neurocognitive skills may be at even greater advantage in speech recognition following exposure to a repeated talker in laboratory- or clinic-based assessments, and potentially in real-world conditions.

Finally, this study sought to determine the relevance of talker adaptation and lexical difficulty to real-world functioning. Although all of the participants in the current study were high-performing on CNC words, they displayed substantial variability in real-world communications skills and QoL. The CNC test was not developed to control for lexical difficulty, and lists vary in lexical characteristics [Bierer et al., 2016]. Consistent moderate to strong relations were observed between the recognition of hard words and both PRESTO and NCIQ scores. Interestingly, accuracy for easy words were not as strongly related to these assessments of real-world functioning. While a strong link between clinical speech recognition scores and QoL has not be uncovered [McRackan et al., 2018; Vasil et al., 2019], examining abilities across different speech perception tasks may have better elucidated the relation between speech perception and QoL outcomes [Luo et al., 2018]. Further, some previous research studies suggest that high-performing CI users display relatively good auditory and neurocognitive skills compared to other CI users [Tamati et al., 2020a] and, as such, may adopt a different perceptual strategy in real-world listening conditions. Therefore, by isolating high-performing adult CI users, we may also observe differing relations among speech perception abilities, auditory and neurocognitive skills, and real-world functioning and uncover aspects of speech perception tasks that more closely relate to patients' real-world experience. In particular, here, the challenge presented by the hard words following adaptation may better reflect the underlying processes that are more relevant to real-world functioning. Therefore, future research should look beyond just the recognition of idealized speech and incorporate tasks involving complex linguistic materials, talkers, and conditions that better reflect everyday listening.

Limitations

The current study was limited in the recruitment of a relatively small sample size ($N = 15$). Although restricted to high-performers, in this small sample, we could not account for all factors that may contribute to variability in word recognition and/or talker adaptation, such as demographics like age [Moberly et al., 2018]. Further, only 3 neurocognitive factors were included. Additional factors, including vocabulary size, should be included in a future study with a larger sample size. Nonetheless, this preliminary study provides some evidence for which auditory and cognitive-linguistic skills may contribute most strongly to spoken word recognition and talker adaptation in adult CI users. Finally, this study was limited to high-performing CI users (CNC >65%), limiting generalizability to adult CI users as a whole. If signal quality is a major factor contributing to talker adaptation, then relatively poorer performers may show even less talker adaptation. Thus, future studies should also include CI users with a broader range of speech recognition outcomes.

Conclusions

Adult CI users demonstrate limited improvement in word recognition following short-term exposure to an unfamiliar talker. Although no improvement was observed for lexically easy words, CI users showed a talker adaptation benefit for hard words. For individual CI users, better signal quality and stronger neurocognitive skills contribute to more accurate recognition of hard words, especially following adaptation and overall talker adaptation. Finally, the processing demands for hard words (vs. easy words), which are not well represented in the clinical CNC test, may better relate to real-world functioning in high-performing adult CI users. Taking into account talker adaptation and lexical difficulty in word recognition tasks – and their relation to real-world functioning – may shed light on the processes involved in real-world listening. This evidence has ramifications for the assessment of speech recognition outcomes and benefit in this clinical population.

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Statement of Ethics

Participants included in this study gave their written informed consent. The IRB of The Ohio State University approved the study protocol for human research, IRB Protocol Number 2015H0173. Animals were not included in this study.

Conflict of Interest Statement

The author A.C.M. received grant support from Cochlear Americas for an unrelated investigator-initiated study of aural rehabilitation and serves as a paid consultant for Cochlear Americas and Advanced Bionics. The author A.C.M. serves as CMO for Otologic Technologies. A.C.M. serves as an associate editor for *Audiology & Neurotology*.

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Author Contributions

The author T.N.T. contributed to design of the study, data acquisition, analysis and interpretation of data, drafting of the manuscript, and final approval of the manuscript. The author A.C.M. contributed to conception of the study, drafting of the manuscript, and final approval of the manuscript. All the authors agree to be accountable for accuracy and integrity of the work.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author T.N.T. (terrin.tamati@osumc.edu) upon reasonable request.

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