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“Product” versus “Process” Measures in Assessing Speech Recognition Outcomes in Adults with Cochlear Implants

Aaron C. Moberly, M.D.[1], **Irina Castellanos, Ph.D.**[1], **Kara J. Vasil, Au.D.**[1], **Oliver F. Adunka, M.D.**[1], and **David B. Pisoni, Ph.D.**[2]

[1]The Ohio State University Wexner Medical Center, Department of Otolaryngology – Head & Neck Surgery, Columbus, Ohio, USA

[2]Indiana University School of Medicine, DeVault Otologic Research Laboratory, Department of Otolaryngology—Head and Neck Surgery, Indianapolis, Indiana, USA

Abstract

Hypotheses—(1) When controlling for age in postlingual adult cochlear implant (CI) users, information-processing functions, as assessed using “process” measures of working memory capacity, inhibitory control, processing speed, and fluid reasoning, will predict traditional “product” outcome measures of speech recognition. (2) Demographic/audiologic factors, particularly duration of deafness, duration of CI use, degree of residual hearing, and socioeconomic status will impact performance on underlying information-processing functions, as assessed using process measures.

Background—Clinicians and researchers rely heavily on endpoint product measures of accuracy in speech recognition to gauge patient outcomes postoperatively. However, these measures are primarily descriptive and were not designed to assess the underlying core information-processing operations that are used during speech recognition. In contrast, process measures reflect the integrity of elementary core sub-processes that are operative during behavioral tests using complex speech signals.

Methods—Forty-two experienced adult CI users were tested using three product measures of speech recognition, along with four process measures of working memory capacity, inhibitory control, speed of lexical/phonological access, and nonverbal fluid reasoning. Demographic and audiologic factors were also assessed.

Results—Scores on product measures were associated with core process measures of speed of lexical/phonological access and nonverbal fluid reasoning. After controlling for participant age, demographic and audiologic factors did not correlate with process measure scores.

Address for correspondence and requests for reprints: Aaron C. Moberly, M.D.; 915 Olentangy River Road, Columbus, OH, 43212. Aaron.Moberly@osumc.edu; Telephone: (614)293-6926; Fax: (614)293-9698.

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Conclusion—Findings provide support for the important foundational roles of information processing operations in speech recognition outcomes of postlingually deaf patients who have received CIs.

Keywords

Cochlear implants; Cognition; Hearing loss; Process measures; Speech perception

Introduction

Clinicians and researchers at cochlear implant (CI) centers rely heavily on endpoint "product" measures of accuracy in speech recognition to gauge patient outcomes postoperatively. These product measures were designed to establish efficacy of devices during the process of obtaining Food and Drug Administration approval, and studies using these product outcome measures consistently reveal enormous variability and individual differences among patients (1–3). Although these product measures are arguably relevant to daily life, based on at least some degree of correlation with patient-reported quality of life measures (4–6), product measures of speech recognition can only demonstrate this outcome variability, typically providing a single percent correct score for a given task. In other words, product measures are primarily "descriptive" in nature; they characterize the state of someone's outcome with a CI. Although these conventional product measures of speech recognition are important because they have clinical utility and strong face validity, they do not help us to understand, explain, or predict outcome variability, nor do they help to inform therapeutic rehabilitative approaches for poor performers, such as audiologic reprogramming of a device, or auditory or cognitive training. As a result, our current therapeutic approaches remain relatively generic in nature – one-size-fits-all; they are not highly effective across a large sample of patients, and they are not equally effective for all individuals.

Product measures of outcomes were not designed to assess the underlying core information-processing operations that are used during speech recognition (7). In contrast, "process" measures of information processing assess the underlying cognitive constructs involved in sensory encoding, information storage and retrieval, verbal rehearsal, and lexical access, and include measures such as processing speed, inhibitory control, capacity of working memory (WM), lexical retrieval, fluid intelligence (reasoning), and comprehension. These functions represent core elementary processing components and subcomponents that reflect system integrity and functionality. Process measures of performance assess elementary core sub-processes that are assumed to be operative in all behavioral tests using complex speech signals as well as other non-speech stimuli, and they ultimately should help to understand performance on conventional product outcome measures. In essence, while product measures are descriptive assessments of outcomes, process measures are "explanatory"; that is, they help us to explain and predict variability in product outcome measures. The current study aimed to explore this hypothesis, by using a number of process measures to assess performance in a group of postlingually deaf adult CI users, and by relating performance on these process measures to more traditional product measures of speech perception. Importantly, all of the process measures incorporated in this study used non-auditory visual stimuli as a means of eliminating the effects of audibility and early auditory sensory coding on performance among participants. This approach effectively allowed us to examine more specifically the contributions of underlying basic cognitive sub-processes that support speech recognition. The use of auditory stimuli during process measures would have made it impossible to determine whether variability in performance among patients was a result of differences in audibility (or auditory processing), or if these differences could be attributed to the cognitive processes of interest.

Although the premise of this study was to explore how process measures of outcome relate to our conventional speech recognition product measures, a number of patient demographic and audiologic factors have been found to correlate (albeit to a lesser degree) with product outcome measures. Specifically, these consistently have included chronological age, duration of deafness, degree of residual hearing prior to implantation, and age at implantation (8–11). An additional goal of the current study was to explore the information-processing mechanisms by which these more traditional demographic/audiologic patient factors contribute to outcomes. At the present time, the core foundational information-processing mechanisms underlying the effects of these demographic/audiologic factors on outcome product measures are unclear. Specifically, we hypothesized that these conventional demographic and hearing history audiologic factors would be associated with underlying information-processing skills, as assessed using our proposed process measures. There is some indirect evidence to support this hypothesis: hearing loss has been associated with cognitive declines (12–14), and these deficits should be captured by our process measures.

When it comes to evaluating process measures in postlingually deaf adults with CIs, many of whom are elderly patients with progressive sensorineural hearing loss, it is also important to keep in mind the effects of cognitive aging on measures of performance. Performance on many cognitive measures has been found to decline with advancing age, even in participants without evidence of dementia or clinical cognitive impairment. For example, older adults typically demonstrate deficits in working memory capacity (15), processing speed (16,17), attentional resources (18), and inhibitory control (19,20). Thus, in the current study, analyses of relations of these process measures to product measures controlled for participant age.

In summary, this study addressed two hypotheses about process measures of outcome following implantation: First, controlling for participant age, process measures of working memory capacity, inhibitory control, processing speed during tasks of rapid lexical/phonological processing, and fluid intelligence would predict product measures of auditory-only speech recognition in postlingually deaf adult CI users. Second, conventional demographic/audiologic factors, particularly duration of deafness, degree of residual hearing, duration of CI use, and socioeconomic status, would be associated with performance on process measures of information-processing functions.

Methods

Participants

Forty-two adult CI users were enrolled and underwent testing. Participants were all native English speakers and had at least a high school diploma or equivalency. All participants were screened for vision using a basic near-vision test and were required to have better than

20/40 near vision, because all of the cognitive measures were presented visually. Two CI participants had vision scores of 20/50; however, they still displayed normal reading scores, suggesting sufficient visual abilities to include their data in analyses. A screening task for cognitive impairment was completed, using the Mini Mental State Examination (MMSE) (21), with a MMSE raw score ≥ 26 required; all participants met this criterion, suggesting no evidence of cognitive impairment. A final screening test of basic word reading was completed, using the Wide Range Achievement Test (WRAT) (22). Participants were required to have a word reading standard score ≥ 75, suggesting reasonably normal general language proficiency. Socioeconomic status (SES) of participants was also collected because it may be a proxy of speech and language abilities. This was accomplished by quantifying SES based on a metric developed by Nittrouer and Burton (23), consisting of occupational and educational levels. There were two scales for occupational and education levels, each ranging from 1–8, with eight being the highest level. These two numerical scores were then multiplied, resulting in scores between 1 and 64. Lastly, a screening audiogram of unaided residual hearing was performed for each ear separately for all participants.

CI users were between the ages of 50 and 83 years and were post-lingually deafened, meaning they should have developed reasonably proficient language skills prior to losing their hearing. Thirty-two (76.2%) participants reported onset of hearing loss no earlier than age 12 years (i.e., normal hearing until the time of puberty). The other 10 (23.8%) reported some degree of congenital hearing loss or onset of hearing loss during childhood. However, all participants had experienced early hearing aid intervention and typical auditory-only spoken language development during childhood, had been mainstreamed in conventional education programs, and had experienced progressive hearing losses into adulthood. All of the CI users received their CIs at or after the age of 35 years. Prior to implantation, all CI users had met candidacy requirements for cochlear implantation, including severe-to-profound hearing loss in both ears. The CI participants were recruited from the patient population of the institution’s Otolaryngology department and had demonstrated CI-aided thresholds in the clinic of better than 35 dB HL across speech frequencies. Duration of hearing loss ranged from 4 to 76, and duration of CI use ranged from 18 months to 34 years. Details of individual CI participants can be found in Table 1. Group mean demographic and screening measure scores for participants are shown in Table 2.

Equipment and Materials

All testing took place at the Eye and Ear Institute of The Ohio State University Wexner Medical Center using sound-proof booths and acoustically insulated rooms for testing. All tests requiring auditory responses were audio-visually recorded for later scoring. Participants wore FM transmitters through the use of specially designed vests. This allowed for their responses to have direct input into the camera, permitting later off-line scoring of tasks. Each task was scored by two separate individuals for 25% of responses to ensure reliable results. Reliability was determined to be >95% for all measures.

Visual stimuli were presented on paper or a touch screen monitor made by KEYTEC, INC., placed two feet in front of the participant. Auditory stimuli were presented via a Roland MA-12C speaker placed one meter in front of the participant at zero degrees Azimuth. Prior to the testing session, the speaker was calibrated to 68 dB SPL using a sound level meter positioned one meter in front of the speaker at zero degrees Azimuth. After the screening measures were completed, the measures outlined below were collected.

Product Measures of Speech Recognition—Speech recognition tasks were presented in the clear over loud speaker. Three speech recognition measures were included to assess perception of speech under three different conditions. These research product measures were selected instead of using clinical stimuli (e.g., AzBio sentences or CNC words) because participants were not familiar with these materials, and because they are challenging enough to avoid ceiling effects for some CI users during testing. The following product measures were used:

1. Harvard Standard Sentences – Sentences were presented via loudspeaker, and participants were asked to repeat as much of the sentence as they could. Thirty sentences from the Harvard Standard lists were used, which were spoken and recorded by a single male talker. The sentences are long, complex, and semantically meaningful, consisting of an imperative or declarative structure (24). An example is "A pot of tea helps to pass the evening." Scores were percentage of total words repeated correctly, as well as percentage of complete sentences repeated correctly, excluding the first two sentences as practice.

2. PRESTO Sentences – These sentences were chosen from the TIMIT (Texas Instruments/Massachusetts Institute of Technology) speech collection, and were created to balance talker gender, keywords, frequency, and familiarity, with sentences varying broadly in speaker dialect and accent (25). PRESTO sentences are high-variability, complex sentences, which would be expected to be more challenging for listeners to recognize. An example of a sentence is "A flame would use up air." Participants were asked to repeat 32 sentences. Scores were again percentage of total words correct, as well as percentage of complete sentences repeated correctly, excluding the first two sentences as practice.

3. CID W-22 wordlists – Fifty CID-W22 words were presented (26). The participants were instructed to repeat the last word that was said after the prompt, "Say the word __." CID W-22 words are phonetically balanced and spoken and recorded by a single male speaker with a general American dialect. Because these are words presented without sentential context, performance should more closely represent sensitivity of the listener to acoustic-phonetic details of speech, as compared with the sentence recognition tasks above. List 1A, which consisted of 50 words, was used for testing. Scores were percentage of whole words correct.

Process Measures of Neurocognitive Functioning

1. Verbal Working Memory Capacity – Visual Digit Span – This task assessed verbal WM capacity of the participants using visual presentation. The digit span task was based on the original auditory digit span task from the Wechsler Intelligence Scale for Children, Fourth Edition, Integrated (27). For this task, participants were presented with a sequence of visual stimuli in the form of digits

(1 through 9) on a computer monitor. To familiarize the participants with the stimuli, one digit appeared on the screen first, followed by a screen with a 3 × 3 matrix of all nine numbers. Participants were asked to touch the digit on the screen that had appeared first. Next, the participants saw a sequence of numerical digits and were asked to reproduce the sequence correctly, via touching the numbers on the computer screen in the correct order, when the screen with all nine numbers appeared. The number of digits presented on each trial began with two stimuli and increased gradually as the participant continued to answer correctly, up to a maximum of seven digits. Each string of digits was presented twice (different stimuli, same string length). When the participant failed to reproduce two strings of the same length correctly, the task automatically terminated. Digits were presented visually one at a time on a computer screen. Once the numbers disappeared from the screen, the participant was asked to touch the numbers on the screen in the correct serial order. Total correct items served as the performance score.

2. Inhibitory Control – Stroop – This computerized task evaluated inhibitory control abilities and is publicly available (http://www.millisecond.com). Participants were shown a color word on the computer screen, presented in either the same or a different color font. The participant was asked to press the computer key on the keyboard that corresponded with the color of the font of the word, not the color name represented by the word. The Stroop task was divided into congruent trials (color and color word matched) and incongruent trials (color and color word did not match). Response times were computed for each condition, and an "interference score" was calculated by subtracting the mean response time for congruent condition from the mean response time for incongruent condition across trials. The interference score from the Stroop is used to assess the amount of inhibitory control needed to carry out the color naming task under conflicting conditions relative to the baseline data with no interference. To do the Stroop task correctly requires active conscious inhibition of the conflicting conditions. Longer response times (slower information processing) are reflected by larger Stroop interference scores.

3. Processing Speed for Lexical/Phonological Access – Test of Word Reading Efficiency, Version 2 (TOWRE) – The TOWRE is a measure of word reading accuracy and fluency, and can be considered an assessment of the speed of a participant's lexical and phonological access (28). The test assesses two types of reading skills: the ability to accurately recognize and identify familiar real words, and the ability to "sound out" non-words via phonologically decoding the non-words. The participants read as many words as they could from the 108-word list in 45 seconds, followed by reading as many non-words as they could in 45 seconds from the 66 non-word list. Two scores were computed: percent whole words correct and percent whole non-words correct.

4. Nonverbal Fluid Reasoning – Raven's Progressive Matrices – A computerized version of the Raven's test was used to assess nonverbal intelligence or reasoning (29). The Raven's presents visual displays of geometric designs in a matrix in

which each design contains a missing piece, and participants must select a response box to complete the pattern. Participants completed as many items as possible in 10 minutes, and scores were total correct number of items.

General Approach

The study protocol was approved by the Institutional Review Board of The Ohio State University. All participants provided informed, written consent, and were reimbursed $15 per hour for participation. Testing was completed over a single 2-hour session, with frequent breaks to prevent fatigue. During testing, CI participants used their typical hearing prostheses, including any contralateral hearing aid, except during the unaided audiogram. Prior to the start of testing, examiners checked the integrity of the individual's hearing prostheses by administering a brief vowel and consonant repetition task, and all participants passed this integrity check.

Data Analyses

To address the first hypothesis, that after controlling for age, process measures of WM capacity, inhibitory control, processing speed, and fluid intelligence would predict traditional product measures of speech recognition, partial correlation analyses were performed while controlling for age. To address the second hypothesis, that demographic/audiologic factors, including duration of deafness, duration of CI use, degree of residual hearing, and SES, would impact performance on process measures, Pearson bivariate correlation analyses were performed.

Results

Group mean scores for product measures of speech recognition and process measures are shown in Table 3. Results demonstrate variability among CI users in both product and process scores. Scores did not differ significantly among patients who used bilateral CIs, a single CI, or a CI plus hearing aid.

The first hypothesis was that when controlling for age, process measures of WM capacity, inhibitory control, processing speed, and fluid intelligence would predict product measures of speech recognition. Table 4 shows results of partial correlation analyses. After accounting for the effects of age, processing speed for both lexical retrieval and phonological access (using the TOWRE-2) and fluid intelligence (using the Raven's) correlated significantly with speech recognition scores across most product measures, partially supporting our first hypothesis.

The second hypothesis was that traditional demographic/audiologic measures would correlate with performance on process measures. Specifically, we predicted that older age at time of testing, longer total duration of hearing loss (computed as current age minus age at onset of hearing loss), and longer duration of hearing loss before CI (computed as age at first CI minus age at onset of hearing loss) would be associated with poorer scores on process measures. In contrast, we expected that longer duration of CI use, greater residual hearing (better ear PTA), and higher SES would correlate positively with performance on process measures. Table 5 shows results of correlation analyses. Notably, for most of our process measures, older age predicted poorer (or slower) performance. For duration of hearing loss, the only significant correlation was between total duration of hearing loss and with speed of lexical access on the TOWRE-2; as predicted, longer duration of deafness was associated with slower lexical access for words. Residual hearing PTA correlated with fluid intelligence, but this was in the opposite direction as predicted; higher PTA (poorer hearing) was associated with higher scores of fluid intelligence. SES was not significantly related to scores on process measures.

Several of the significant correlations observed between process measures and demographic/audiologic factors were in the opposite direction of what was predicted, and this deserved further exploration. Because the above analyses also suggested that older age was generally associated with poorer performance across most of our process measures, a new set of analyses was performed to investigate the association of process measures with our demographic/audiologic measures, after controlling for the effects of age. Results of these partial correlation analyses are shown in Table 6. After controlling for age, none of the partial correlations remained significant between process measures and demographic/audiologic measures, suggesting the important contribution of age in this clinical sample.

Discussion

This study of product and process measures following implantation explored two general questions about speech recognition outcomes in postlingual adults with CIs: (1) Do process measures of information processing predict performance on conventional speech recognition product measures, after controlling for participant age? (2) Do demographic and audiologic factors that have previously been found to correlate with speech recognition outcomes relate to performance on process measures?

With regard to the first question, we found that two process measures correlated significantly with traditional product measures: speed of lexical/phonological access on the TOWRE-2 was related to speech recognition for all three types of speech materials tested. Fluid intelligence as assessed using the Raven’s task was also related to scores on all three speech recognition tests. It is important to keep in mind that the process measures reported here were obtained from information-processing tasks that used a non-auditory visual presentation format, such that performance across individual participants would not be affected by differences in audibility or early auditory sensory registration and encoding. The emphasis in past studies of CI outcomes has focused mostly on sensory factors and audibility restored to the listener through a CI, rather than on cognition and information-processing abilities of the listener. The present findings using visually-based process measures suggest that these core abilities play significant roles in the outcomes of adult CI users, and that process measures may help us to understand the enormous individual differences and variability consistently demonstrated on traditional endpoint outcome product measures of speech recognition.

Interestingly, several process measures were related significantly to demographic and audiologic measures. However, after controlling for participant age, all of these effects were no longer significant. Understanding the effects of aging on process measures in adult CI users will require further studies using additional measures, but the present findings are consistent with previous work linking cognitive declines, aging, and speech recognition outcomes for CI users (30,31).

There are some limitations to the current study. First, due to time constraints, only a few process measures were selected for testing. We selected those measures that theoretically represented elementary core sub-processes that are assumed to be required during speech processing and that would be simple to measure using visual stimuli. Future studies will expand on these to include additional cognitive processing measures. Second, the intentional use of visual process measures implies the assumption that cognitive processes are modality-general; that is, the information processing mechanisms are assumed to be the same for visual and auditory sensory input. This assumption is reasonable but has not been proven in this study.

Conclusions

The findings from this study suggest that "process" measures of underlying information-processing skills obtained using non-auditory neurocognitive visual information-processing tests may provide new clues to the underlying mechanisms responsible for the enormous variability and individual differences demonstrated by adult CI listeners on traditional end-point "product" measures of speech recognition used clinically. Moreover, performance on these process measures appears to be related to patient age. Findings provide further support for the important foundational roles of neurocognitive information-processing operations related to the encoding, storage, and retrieval of verbal information in postlingually deaf patients who have received CIs as a medical intervention for severe-to-profound hearing loss.

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Table 1

Participant demographics.

Participant	Gender	Age (years)	Implantation Age (years)	SES	Side of Implant	Hearing Aid	Etiology of Hearing Loss	Better ear PTA (dB HL)
1	F	65	54	24	Bilateral	No	Genetic progressive	120
2	F	66	62	35	Right	Yes	Progressive loss as adult, noise exposure	78.75
3	F	67	58	12	Right	Yes	Genetic, progressive as an adult	103.75
4	F	55	44	15	Left	No	Sudden, otosclerosis, progressive as an adult	120
5	M	70	65	30	Right	No	Genetic, progressive as an adult	88.75
6	M	60	52	36	bilateral	No	Measles	105
7	F	57	48	25	Right	Yes	Genetic, progressive as a child	82.5
8	M	79	76	48	Right	Yes	Progressive as adult, noise exposure	70
9	F	69	56	10.5	Bilateral	No	Otosclerosis, progressive as adult	112.5
10	M	55	50	30	Bilateral	No	Progressive loss as adult	120
11	F	76	68	30	Left	No	Progressive loss as adult, probable autoimmune	108.75
12	M	79	74	10	Left	No	Unknown	108.75
13	F	81	71	30	Right	No	Progressive as adult, sudden hearing loss	88.75
14	M	59	57	24	Bilateral	No	Sudden hearing loss	120
15	M	78	72	12.5	Bilateral	No	Progressive loss as adult	120
16	M	69	62	56	Bilateral	No	Genetic, progressive loss as child	120
17	F	50	35	32.5	Bilateral	No	Progressive loss as child	117.5
18	F	64	61	30	Right	No	Progressive loss as adult	103.75
19	F	67	58	9	Bilateral	No	Meniere’s disease	120
20	M	83	76	42	Right	Yes	Progressive loss as adult, noise exposure	68.75
21	F	73	67	15	Right	No	Progressive loss as child	98.75
22	M	76	73	49	Left	Yes	Progressive loss as adult, noise exposure	72.5
23	F	79	45	15	Right	Yes	Progressive loss as adult	57.5
24	M	74	72	64	Right	Yes	Congenital	92.5
25	M	66	60	18	Left	No	Meniere’s disease	80
26	M	77	75	15	Bilateral	No	Chronic ear infections, cholesteatoma	105
27	F	65	63	36	Right	No	Genetic, progressive as adult	86.25
28	F	62	59	14	Bilateral	No	Sepsis, ototoxic medications	95
29	M	80	79	9	Left	No	Genetic, progressive as adult, noise exposure	76.25

Participant	Gender	Age (years)	Implantation Age (years)	SES	Side of Implant	Hearing Aid	Etiology of Hearing Loss	Better ear PTA (dB HL)
30	M	61	55	24	Right	Yes	Unknown	111.25
31	M	60	55	10.5	Left	No	Genetic, progressive as adult	115
32	F	64	59	24	Left	Yes	Progressive as a child	95
33	M	59	54	6	Right	No	Genetic, progressive as adult	108.75
34	M	57	55	6	right	No	Genetic, progressive as adult	101.25
35	M	65	38	12	Right	Yes	Progressive as adult, noise exposure	92.5
36	M	50	35	25	Bilateral	No	Genetic, progressive as adult	120
37	M	81	80	49	Left	Yes	Progressive as adult	75
38	M	70	68	42	Left	Yes	Progressive as adult	93.75
39	M	53	36	20	Bilateral	No	Progressive as adult	120
40	F	64	61	28	Right	Yes	Meniere's disease	22.5
41	F	74	72	35	Left	Yes	Genetic, progressive as adult	60
42	M	68	65	30	Right	No	Progressive as adult, noise exposure	100

Notes: SES: socioeconomic status; PTA: pure-tone average across 500, 1000, 2000, and 4000 Hz; HL: hearing level

Table 2

Participant demographics for cochlear implant (CI) users; MMSE: Mini-Mental State Examination; SES: socioeconomic status

	Participants (*N* = 42)	
	Mean	***(SD)***
Demographics		
Age (years)	67.3	*(9.1)*
Total duration of hearing loss (years)	39.1	*(19.9)*
Duration of hearing loss before CI (years)	32.2	*(19.8)*
Age at first CI (years)	60.1	*(12.0)*
Duration of CI use (years)	7.2	*(6.7)*
Reading (standard score)	98.0	*(12.1)*
MMSE (raw score)	28.6	*(1.3)*
SES	26.2	*(14.3)*

Table 3

Group mean "product" measure scores of speech recognition and "process" measure scores of neurocognitive functions for cochlear implant users.

	Participants (*N* = 42)	
	Mean	***(SD)***
Product Measures - Speech Recognition		
Harvard Standard Sentences (% words correct)	72.1	*(18.3)*
Harvard Standard Sentences (% full sentences correct)	42.3	*(23.6)*
PRESTO Sentences (% words correct)	56.1	*(24.5)*
PRESTO Sentences (% full sentences correct)	24.2	*(20.9)*
CID W-22 Words (% words correct)	66.7	*(22.4)*
Process Measures - Neurocognitive Functions		
Digit Span (total correct)	43.1	*(16.8)*
Stroop Interference (msec)	296.6	*(289.8)*
TOWRE-2 Words (percent correct)	71.3	*(11.9)*
TOWRE-2 Non-words (percent correct)	62.8	*(17.8)*
Raven's Nonverbal Fluid Reasoning (total correct)	9.7	*(5.0)*

Table 4

Partial correlation *r* values for analyses between product measure scores of speech recognition and process measure scores of neurocognitive functions, controlling for participant age.

Partial r, controlling for participant age	**Product Measure (Speech Recognition)**				
	Harvard Standard Sentences (% words correct)	**Harvard Standard Sentences (% full sentences correct)**	**PRESTO Sentences (% words correct)**	**PRESTO Sentences (% full sentences correct)**	**CID W-22 Words (% words correct)**
Process Measures - Neurocognitive Functions					
Digit Span (total correct)	.12	.26	.08	.17	.09
Stroop Interference (msec)	−.13	−.23	−.05	−.08	−.12
TOWRE-2 Words (percent correct)	**.37** *	**.57** **	**.47** **	**.54** **	**.47** **
TOWRE-2 Non-words (percent correct)	.21	**.45** **	.28	**.40** *	.22
Raven's Nonverbal Fluid Reasoning (total correct)	.27	**.39** *	**.45** **	**.47** **	**.35** *

* p-value < 0.05

** p-value < 0.01

Table 5

Pearson's bivariate correlation *r* values for analyses between process measure scores and demographic/audiologic measures for cochlear implant (CI) users; PTA: pure-tone average; HL: hearing level; SES: socioeconomic status

Pearson's *r*	**Age (years)**	**Total duration of hearing loss (years)**	**Duration of hearing loss before CI (years)**	**Duration of CI use (years)**	**Better ear PTA (dB HL)**	**SES**
Process Measures - Neurocognitive Functions						
Digit Span (total correct)	−.06	.18	.22	−.13	−.14	.21
Stroop Interference (msec)	**.38** *	.08	.09	−.03	−.08	−.07
TOWRE-2 Words (percent correct)	−.22	**−.35** *	−.28	−.16	−.02	.15
TOWRE-2 Non-words (percent correct)	**−.34** *	−.07	−.05	−.05	.08	.05
Raven's Nonverbal Fluid Reasoning (total correct)	**−.64** **	−.03	−.05	.06	**.38** *	−.04

* p-value < 0.05

** p-value < 0.01

Table 6

Partial correlation *r* values for analyses between process measure scores and demographic/audiologic measures for cochlear implant (CI) users, after controlling for the effects of age; PTA: pure-tone average; HL: hearing level; SES: socioeconomic status

Partial r, controlling for participant age	**Total duration of hearing loss (years)**	**Duration of hearing loss before CI (years)**	**Duration of CI use (years)**	**Better ear PTA (dB HL)**	**SES**
Process Measures - Neurocognitive Functions					
Digit Span (total correct)	.14	.19	−.16	−.22	.19
Stroop Interference (msec)	.09	−.13	.13	−.14	−.27
TOWRE-2 Words (percent correct)	−.30	−.21	−.23	−.10	.24
TOWRE-2 Non-words (percent correct)	−.07	−.03	−.10	−.10	.14
Raven's Nonverbal Fluid Reasoning (total correct)	.02	.04	−.06	.15	.14

* p-value <0.05

** p-value <0.01