Speech rate, rate-matching, and intelligibility in early-implanted cochlear implant users

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An important speech-language outcome for deaf people with cochlear implants is speech intelligibility—how well their speech is understood by others, which also affects social functioning. Beyond simply uttering recognizable words, other speech-language skills may affect communicative competence, including rate-matching or converging toward interlocutors' speech rates. This initial report examines speech rate-matching and its relations to intelligibility in 91 prelingually deaf cochlear implant users and 93 typically hearing peers age 3 to 27 years. Live-voice spoken sentences were repeated and later transcribed by multiple hearing listeners. Speech intelligibility was calculated as proportions of words correctly transcribed. For speech rate-matching measures, speech rates (syllables/s) were normalized as percentages faster or slower than examiners' speech rates. Cochlear implant users had slower speech rates, less accurate and less consistent rate-matching, and poorer speech intelligibility than hearing peers. Among cochlear implant users, speech rate and rate-matching were correlated with intelligibility: faster talkers and better rate-matchers were more intelligible. Rate-matching and intelligibility improved during preschool, with cochlear implant users delayed by about a year compared to hearing peers. By school-age, rate-matching and intelligibility were good overall, but delays persisted for many cochlear implant users. Interventions targeting rate-matching skills are therefore warranted in speech-language therapy for this population. © 2017 Acoustical Society of America.

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I. INTRODUCTION

Speech intelligibility, or how well one's speech can be recognized by others, is a core speech-language outcome for deaf people with cochlear implants (CIs), who often show large individual differences in both receptive and expressive speech-language skills (Geers, 2002; Ertmer, 2007; Niparko *et al.*, 2010; Pisoni *et al.*, 2008; Sarant *et al.*, 2001). Speech intelligibility can be assessed using several methods (Ertmer, 2011); one of the most common methods is playback-transcription, in which audio recordings are orthographically transcribed by multiple listeners. To achieve good intelligibility, many foundational components of spoken language must be mastered, including control of articulation, breathing, and intonation (Chin *et al.*, 2012; Ertmer, 2011; Monsen, 1978). Another component is speech rate.

Previous work has shown relations between speech rate and speech intelligibility, with many studies reporting that deliberately produced “clear” speech styles with characteristic slow speech rates were easier to understand (e.g., Krause and Braida, 2002; Picheny *et al.*, 1985, 1986), and other studies reporting that speech slowed via signal processing was harder to understand for young adults (Dagenais *et al.*,

2006; Nejime and Moore, 1998) but easier for elderly listeners (Lessa and Costa, 2013). In one study, CI users with slower speech rates were harder to understand (Pisoni *et al.*, 1999). Other research has found no direct relation between speech rate and intelligibility (Bradlow *et al.*, 1996; Yorkston and Beukelman, 1981). The test conditions for talkers and listeners in these studies varied. Although all the speech evaluated in these studies consisted of read or repeated sentences, some used professional speakers who were coached to produce different styles or speech rates, while others used differing numbers of uncoached adults or children, some comparing talkers with hearing loss or speech disorders to those without. Listeners varied across studies from young adults to elderly, with or without hearing loss, who heard one talker or many, and speech-presentation conditions were either in quiet or with added noise or distortion simulating hearing loss.

The differences between such studies and their results highlight the importance of communicative context. That is, an appropriate speech rate for one task or situation may not be appropriate in a different setting (e.g., reading for clarity vs natural conversation, with strangers vs family, in quiet vs in a noisy restaurant, to show empathy vs excitement, etc.), and mismatches between speech rates and listeners' expectations may make perceptual processing and recognition more difficult (just as it does for mismatches with expected talker identity, Magnuson and Nusbaum, 2007; Rubin, 1992). Thus, not only

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speech rates, but also *appropriate* speech rates for the communicative context likely contribute to speech intelligibility.

One way to assess the appropriateness of a speech rate in context is to observe the behavior of interlocutors or others in the communicative situation. Previous work has shown that interlocutors in a variety of settings converge toward each other's speech patterns for many acoustic measures, including changes in vowel formants (Babel, 2012; Pardo, 2010), pitch, intensity, voice quality (Levitan and Hirschberg, 2011), and speech rate (Borrie and Liss, 2014; Pardo *et al.*, 2013; Putman and Street, 1984), among others (see Pardo, 2013, for a review). Under Communication Accommodation Theory, this convergence (also known as entrainment) serves to reduce social distance and build rapport between interlocutors (Giles and Powesland, 1975; Putman and Street, 1984). It also aids in speech processing and comprehension (Pickering and Garrod, 2004). Similarly, divergence in speech patterns can be used to create or reflect social distance, signaling dislike or disagreement with an interlocutor (Bourhis and Giles, 1977; Giles *et al.*, 1987). Thus, inadequate convergence in speech rate may be interpreted by interlocutors as expressing negative attitudes, disinterest, rudeness, or communicative incompetence (Apple *et al.*, 1979; Putman and Street, 1984). In this way, appropriate speech rate contributes not only to speech intelligibility but also to judgments about the speaker's personality or communicative abilities, which in turn affect social interaction, friendships, self-image, and so on.

The present study examined a foundational skill necessary for successful speech-rate convergence, the rapid adaptation to local changes in interlocutor speech rate, which we call *speech rate-matching*. Rather than use a free-flowing conversational setting with uncontrolled turn lengths, this study focused on local effects by using sentence-repetition tasks in which an experienced speech-language pathologist examiner orally produced simple sentences with naturally varying speech rates, and CI users and typically hearing (TH) peers repeated each sentence aloud, directly following each model sentence. The speech rates of the responses and model sentences were compared with several measures that were created to assess rate-matching, and both raw speech rate and rate-matching measures were examined for their contributions to speech intelligibility in CI and TH samples.

A. Research questions and hypotheses

The purpose of the present study was twofold: (1) to compare CI and TH samples on patterns of speech rate and speech rate-matching, and (2) to assess the relations between these measures and speech intelligibility. These purposes formed the research questions below and organized the study's results, which were replicated in two data sets: CI and TH preschoolers who were tested in two consecutive years as part of an on-going longitudinal study and an older set of long-term CI users and TH controls ranging from school-age through young adulthood who were tested once. Speech intelligibility measures from both data sets were reported in previous work (Freeman *et al.*, 2017; Montag *et al.*, 2014) and were found to be lower and more variable among CI users

than TH controls. If speech rate and speech rate-matching contribute to speech intelligibility in a consistent way, these measures should also be poorer and more variable in CI users, with less intelligible CI users showing especially poor rate-matching performance. To test this general hypothesis, we compared CI and TH patterns within and across data sets following predictions for each research question.

1. Research question 1: How do CI and TH samples compare on speech rate and speech rate-matching?

We hypothesized that CI users would have slower speech rates and poorer rate-matching than TH peers. In addition, more variation was expected among CI users than TH peers, meaning that some CI users would show good performance, but others might show very poor performance. In the preschool samples, improvement in rate-matching was expected between annual testing times for both CI and TH samples, with the likelihood that CI users would be especially delayed at the earliest testing time (as in Freeman *et al.*, 2017). Preschoolers were also expected to show poorer rate-matching performance than older samples.

2. Research question 2: How are speech rate and rate-matching related to speech intelligibility?

We hypothesized that speech rate and rate-matching would show positive correlations with speech intelligibility, so that more intelligible talkers would display faster speech rates and more accurate and consistent rate-matching than less intelligible talkers. We also expected that these correlations would be stronger among CI users than TH participants, who showed high intelligibility in both data sets (Freeman *et al.*, 2017; Montag *et al.*, 2014).

II. METHOD

A. Participants

Participants were enrolled in two long-running investigations of prelingually deaf cochlear implant users. The preschool data set was drawn from the first two annual testing sessions in a longitudinal study (described in Beer *et al.*, 2014; Kronenberger and Pisoni, 2014), and the older-participant data set was drawn from one testing session in a study of long-term outcomes in CI users (Kronenberger *et al.*, 2013). CI participants in both sets were recruited from patient populations receiving services at a university hospital-based CI clinic and the surrounding community. TH control samples were recruited through advertisements in the same hospital and community. No participant appeared in both data sets.

The cochlear implant samples consisted of 28 preschoolers and 63 older CI users who met the following inclusion criteria: (1) severe-to-profound bilateral hearing loss (>70 dB hearing loss in the better-hearing ear), (2) consistent use of a multichannel CI system with an up-to-date processor, (3) a primarily English home environment, (4) current or prior enrollment in an aural rehabilitative program that encourages the development of speaking and listening skills, (5) no additional developmental or cognitive delays. The following additional inclusion criteria differed between

the data sets: (6) onset of deafness identified during infancy for preschoolers but up to 2 years of age for the older set, (7) CI implantation by age 3 years for preschoolers but by age 7 years for older CI users, (8) age at time of first testing between 3;0 and 6;11 years for preschoolers but at least 7;6 for the older set (with no upper limit), and (9) length of CI use at least 6 months for preschoolers but at least 7 years for the older set of long-term CI users. (Note that we use “preschool” as a term of convenience to describe the younger data set, even though some children in this group may have entered school.) Intelligibility scores for preschoolers were drawn from one or both of two consecutive annual testing times; 18 had speech intelligibility scores available from both testing times, 7 had scores from time 1 only, and 3 had scores from time 2 only.

The TH control samples consisted of 30 preschoolers and 63 older participants with typical hearing (pure-tone average in the normal range and no history of hearing aid use). They fit the same age ranges as CI users, reported no developmental or cognitive delays, and resided in monolingual English-speaking homes. All 30 preschoolers had speech intelligibility scores from time 1, but only 27 had scores from time 2.

Table I summarizes demographic and CI device information for all samples with *N*s, means, and ranges. Within each data set, demographic characteristics were comparable between CI and TH samples, with no significant differences in age, nonverbal IQ, or family income (two-tailed Welch’s *t*

tests, all $p > 0.05$), although there were slightly more males in all samples except older TH, in which there were more females. Across data sets, the older CI users had used their CIs longer [$t(81.62) = -17.45, p < 0.001$], were implanted at older ages [$t(88.71) = -5.65, p < 0.001$], and had slightly greater pre-implant hearing loss [$t(37.55) = -2.09, p < 0.05$] than the preschool CI users, but nonverbal IQ and family income did not differ across data sets. The CI samples also did not differ in age of onset of deafness or communication mode (all $p > 0.05$).

B. Procedure

Testing was conducted by one of two female licensed speech-language pathologists (SLPs) experienced in testing deaf children and adults with CIs. Protocols were approved by the university’s institutional review board, and participants or their parents were consented prior to testing. During testing sessions, parents and adult participants reported demographic information (see Table I), and participants completed several performance tests of speech-language skills, including the sentence-repetition tests of intelligibility described below.

C. Measures

Different age-appropriate tests of intelligibility were used for each data set: BIT for preschoolers and McGarr for

TABLE I. Sample descriptions.^a

Variable	Preschool		Older	
	CI	TH	CI	TH
Total <i>N</i>	28	30	63	63
<i>N</i> at time 1/time 2	25/21	30/25		
Sex (<i>N</i> ; male/female)	16/12	16/14	35/28	27/36
Nonverbal IQ ^b at time 1	54.0 (33–81)	59.7 (41–81)	55.3 (32–68)	56.0 (40–70)
Family income ^c at time 1	6.9 (1–10)	7.2 (1–10)	7.2 (2–10)	7.2 (1–10)
Age at time 1 (years)	4.4 (3.1–6.9)	4.2 (3.1–7.0)	15.1 (7.8–27.4)	15.2 (7.1–25.3)
Age at time 2 (years)	5.4 (4.1–7.9)	5.0 (4.1–7.2)		
Age change time 1–2 (years)	1.0 (0.5–1.3)	1.0 (0.6–1.5)		
Years of CI use at time 1	2.8 (0.8–5.2)		12.1 (7.1–22.4)	
Years of CI use at time 2	3.9 (1.5–6.1)			
Onset of deafness (months)	0.1 (0–2.0)		2.9 (0–36.0)	
Age at implantation (months)	19.3 (8.0–36.6)		35.8 (8.3–75.8)	
Best pre-implant PTA	101.3 (73.3–118.4)		107.6 (85.0–118.4)	
Communication mode ^d	4.9 (2–5)		4.7 (1–5)	
Bilateral CI (<i>N</i> ; time 1/2)	19/16		27	
CI model/processing strategy (<i>N</i>)				
CC Nucleus / ACE	23		37	
CC Nucleus / SPEAK			11	
ABC Clarion / HiRes	3		2	
ABC Clarion / MPS			3	
ME Opus II / FSP	1		1	
ME Opus II / CIS			3	
(missing data)			6	

^aValues are means (ranges), unless otherwise indicated. PTA = pure tone average (dB hearing loss); TC = Total Communication (speech + sign); CC = Cochlear Corporation; ACE = Advanced Combination Encoder; SPEAK = Spectral Peak; ABC = Advanced Bionics Corporation; HiRes = High Resolution; MPS = Multiple Pulsatile Stimulation; ME = Med-El Corporation; FSP = Fine Structure Processing; CIS = Continuous Interleaved Sampling.

^bNonverbal IQ: Study 1: T-score from the Wechsler Abbreviated Scale of Intelligence Matrix Reasoning subtest; Study 2: T-score from the Differential Ability Scales, II Picture Similarities subtest.

^cIncome coded on a 1–10 scale (<\$5,000/year to >\$95,000/year).

^dCommunication mode coded on a 1–6 scale (mostly sign to auditory-oral) (Geers, 2002).

older participants. The same five speech rate and rate-matching measures were used for all participants.

1. BIT (preschooler speech intelligibility)

The Beginner's Intelligibility Test (Osberger *et al.*, 1994) is a sentence-repetition task that was created for use with young (preliterate) children with hearing loss. It was used with preschoolers in the present study and has been used with deaf children with CIs in previous work (Castellanos *et al.*, 2014; Chin *et al.*, 2012; Ertmer, 2007, 2011; Osberger *et al.*, 1994). The BIT consists of four lists of ten simple sentences, each with two to six words that are familiar to young children (e.g., "The bear sleeps. My airplane is small."). One list is used per testing session, during which the examiner produces a sentence aloud and the child repeats the same sentence aloud. Because the focus of the BIT is on intelligibility, speech rate is not an explicit component; examiners did not attempt to produce any particular or consistent speech rate, and participants were not instructed to imitate any aspect of the examiner's speech patterns beyond repeating the words of each modeled sentence. Thus, variations in examiner speech rate are naturally occurring rather than manipulated experimentally, and the speech-rate matching performance of participants is treated here as a reflection of their ability to adapt rapidly to local variations in speech rate, rather than to converge over time toward a constant, experimentally controlled rate.

In our study, the BIT was typically administered about halfway through a 2-hour testing session that included frequent breaks between various linguistic, cognitive, and behavioral tests, with parents observing in the same or an adjoining room. Examiners began with simple instructions (e.g., "I'm going to read some sentences; I want you to listen and repeat them back to me") and prompted children between sentences as needed (e.g., "You say what I say. Ready?") BIT sessions were audio recorded in a quiet room directly to a solid-state digital recorder using a table-top microphone set about 18 inches from the child's mouth. The children's sentences were digitally extracted, amplitude-normalized to minimize variations in loudness, and stored for later playback, transcription, and scoring.

Intelligibility was scored for each sentence and each participant as the mean percentage of words correctly identified via orthographic transcription by five or six naive TH listeners. Listeners were 23 undergraduate native speakers of American English who received partial course credit for participation, reported no prior experience with deaf speakers or CI users, and passed a hearing screening and orthographic transcription screening. Each listener heard only CI users or TH participants from one testing time (2 participant groups $\times$ 2 testing times $\times$ 6 listeners each = 24 transcribers, with one later removed after discovering that he was a non-native English-speaker). Seated at a computer with sentences presented over high-quality headphones, listeners orthographically transcribed what they thought the child said after each sentence. The percentages of words correctly identified in a sentence were averaged across transcribers for each sentence intelligibility score, and the mean participant intelligibility

score for the testing session was calculated as the mean of all the child's sentence scores. Because many children did not repeat every word or morpheme of each modeled sentence, scores were calculated against only the words that the child attempted to produce, not the complete modeled sentence (Ertmer, 2007; Freeman *et al.*, 2017). For example, transcriptions for a modeled sentence like "The baby cries" repeated as "Baby cry" would not consider the missing "the" and -s morpheme.

2. McGarr sentences (older speech intelligibility)

The McGarr Sentence Intelligibility Test (McGarr, 1981) is a sentence-repetition task, similar to the BIT but created for use by people with hearing loss school-age and older; it has also been implemented with CI users in previous work (e.g., Geers, 2002; Montag *et al.*, 2014; Tobey *et al.*, 2011). Participants repeat 36 short sentences (e.g., "The flag is red, white, and blue," "Get the cake") which are printed individually on index cards and modeled orally. The McGarr test was administered and recorded following the same procedures as those used for the BIT, except that each printed sentence was visible to the participant while the examiner also read it aloud and the participant repeated it.

Sentence intelligibility and *mean participant intelligibility* were calculated as they were for the BIT, but using three transcribers for CI users and one transcriber for TH controls, with each transcriber hearing all 36 sentences from only one talker. Because mean participant intelligibility scores were above 90% for nearly all TH and about two-thirds of CI participants in the older data set, a stricter method of scoring was developed. This *perfect-sentence intelligibility* measure was the percentage of a participant's sentences which were perfectly transcribed by all listeners. Scores from this method were very highly correlated with the conventional mean participant scores [$r(124) = 0.87$, $p < 0.001$], but with ranges of 69%–94% for TH and 3%–81% for CI users, patterns were clearer without the ceiling effect from the conventional scoring method of averaging sentence scores.

3. Rate measures

Speech rate and rate-matching were assessed using the following five measures, detailed below:

- *Raw speech rate* for each participant sentence (syllables/s).
- *Normalized speech rate* (% of SLP's speech rate) for each sentence, averaged across sentences for each participant.
- *Distance from SLP rate* (also known as *rate-distance*), the absolute value of the normalized rate for each sentence, averaged across sentences for each participant.
- *Rate variability* for each participant (SD of participant's normalized sentence rates).
- *Correlation with SLP rate* (also known as *SLP-correlation*) for each participant (Pearson's r between all the participant's speech and all the SLP's speech, presented after raw speech rate in Sec. III).

The *raw speech rate* for each participant sentence was measured in syllables per second, with the number of

syllables uttered verified by the first author in order to disregard any examiner reading errors or omissions in participant repetitions. To assess participants' ability to match or approximate the speech rates of the SLP examiners (speech rate-matching), four additional measures were calculated with reference to the SLPs' speech rates (also in syllables/s).

The two SLPs who served as test examiners in the present studies did not differ in overall speech rate, but they spoke faster to TH than CI participants in both samples, and faster to older participants than preschoolers, and their rates were related to sentence length and presentation order. To take such incidental variation into account, a *normalized speech rate* for each participant sentence was calculated as a percentage of the corresponding SLP model sentence rate, which was set to 0 so that a normalized rate of 20%, for example, indicated a participant speech rate 20% faster than the SLP rate, and -20% indicated a participant rate 20% slower than the SLP rate.

Normalized speech rate also served as the initial basis for developing a measure of speech rate-matching performance in terms of distances from the SLP rates. In this study, normalized rates within 10% of SLP rates (i.e., between -10% and 10%) were considered "on-target" or good rate-matching, and those more than 10% faster or slower than SLP rates were considered "off-target" or poor rate-matching. Although a $\pm 10\%$ cutoff may seem strict, sufficient numbers of participants fell within the target range to verify its utility in the current analyses. A measure of *distance from SLP rates* (or *rate-distance*) was also calculated for each sentence as the absolute value of its normalized rate, so that a distance of 15%, for example, would indicate that a sentence was repeated 15% off-target, i.e., faster or slower than the SLP model rate.

While raw speech rate, normalized speech rate, and rate-distance were calculated for each sentence and then summarized across sentences for each participant, two additional rate-matching measures were calculated only across each participant's sentences. *Rate variability* was calculated for each participant as the standard deviation of his/her normalized sentence rates, and the *correlation with SLP rates* (or *SLP-correlation*) was calculated (Pearson's r) between his/her raw sentence rates and the raw rates of the sentences modeled for him/her by the SLP. Because SLP-correlation was derived from raw speech rates rather than normalized rates, results for SLP-correlations will be presented after those for raw speech rate.

D. Data analysis

Welch's t tests, which do not assume equal variance between samples (and which report non-integer degrees of freedom), were used to assess relations among measures between groups of participants. Pearson correlations were used to relate measures within groups of participants. Partial correlations were used to assess the contributions of rate-matching to intelligibility beyond the effect of raw speech rate. Because prior literature has reported rate-intelligibility relations in both directions (e.g., slower speech being more or less intelligible), and because there has been little prior

work published on speech rate in CI users compared to TH peers, all statistical tests were two-tailed, and *a priori* assumptions of directionality were avoided. In cases of multiple comparisons (e.g., Table III), alpha levels were corrected across all correlations made within each sample (CI, TH) and speech intelligibility measure (mean participant, sentence, perfect-sentence) using false discovery rate control (Benjamini and Hochberg, 1995), which controls the expected incidence of false positives without unduly reducing statistical power.

Because the participants in the older data set covered a wide age range from early school-age through young adulthood, differences were explored between three age groups: child (age 7–12 years, $N = 20$ CI, 17 TH), teen (age 13–17 years, $N = 26$ CI, 29 TH), and adult (age 18–27 years, $N = 18$ CI, 16 TH). However, age was not a significant factor in the analyses, and age groups did not differ on most measures. Therefore, results are reported for all ages combined, and any differences between age groups will be noted as necessary.

III. RESULTS

A. Research question 1: Compare CI and TH on rate measures

CI and TH samples were compared to test the hypotheses that CI users would have slower speech rates and poorer and more variable speech rate-matching than TH controls. Table II summarizes participant rate measures (M , SD) for each sample and the raw speech rate of SLPs when modeling sentences for each sample. As detailed below, the CI samples in both data sets showed slower speech rates, less accurate and less consistent rate-matching, and greater variation in all measures than the TH samples. Across data sets, performance in all measures was generally better in the older samples than the preschool samples; CI preschoolers at time 1 were especially delayed in performance. (Note that significant p -values for t tests are reported in the text; see Table VII in the Appendix for the corresponding t -statistics and degrees of freedom.)

1. Raw speech rate

The two SLPs who administered the speech intelligibility tests did not differ significantly in raw speech rate, but they spoke more slowly to CI users in each data set (both $p < 0.05$), particularly to CI preschoolers at time 1, and more slowly to preschoolers than older participants ($p < 0.001$; see Table II).

In both data sets (and within each preschool testing time), TH participants' raw speech rates were faster than CI users' rates (both $p < 0.001$). Within each preschool CI or TH sample, mean rates did not differ significantly between testing times, and CI rates at time 2 did not differ from TH rates at time 1, but CI rates at time 1 were slower than TH rates at time 2 ($p < 0.001$), suggesting a delay of about a year for preschool CI users. Across data sets, the older samples spoke faster than the preschoolers ($p < 0.001$).

To assess the degree of rate-matching to SLP rates, Welch's t tests were used to compare the distributions of mean participant speech rates in each group and the mean

TABLE II. Rate measures by sample and testing time.^a

Speech rate measure	Preschool				Older	
	CI		TH		CI	TH
	Time 1	Time 2	Time 1	Time 2		
SLP raw rate (syllables/sec)	2.8 (0.3)	3.0 (0.3)	3.0 (0.2)	3.0 (0.2)	3.4 (0.2)	3.7 (0.3)
Participant measures						
Raw rate (syllables/sec)	2.5 (0.4)	2.7 (0.5)	2.8 (0.4)	2.9 (0.4)	3.4 (0.6)	3.8 (0.4)
Correlation with SLP rate (r)	0.50 (0.4)	0.67 (0.3)	0.77 (0.2)	0.82 (0.2)	0.67 (0.2)	0.78 (0.1)
Normalized rate (% of SLP rate)	-11.4 (10.8)	-8.9 (10.6)	-7.4 (9.8)	-2.2 (9.5)	-2.0 (14.0)	3.6 (6.5)
Distance from SLP rate (%)	21.6 (9.2)	15.6 (7.1)	14.8 (6.5)	12.7 (5.4)	14.9 (7.5)	10.9 (3.3)
Rate variability (normalized rate SD)	20.8 (12.8)	13.9 (4.6)	14.1 (5.8)	11.9 (5.2)	13.8 (3.1)	12.3 (2.5)

^aValues are means (SDs). SLP rate: rate used by speech-language pathologists when modeling sentences for each participant group. Normalized rate: percentage faster/slower than SLP model sentence rates.

rates of SLPs when talking to that group. Among preschoolers, only TH rates at time 2 equaled SLP rates ($p > 0.1$); rates for the other three groups were significantly slower than SLP rates (all $p < 0.05$). However, both older samples matched SLP rates ($p > 0.1$).

2. Correlation with SLP rates

Among preschoolers, the correlations between raw participant and SLP rates were high for TH and lower and more variable for CI (Table II). Within each testing time, SLP-correlations were significantly stronger for TH than CI participants (both $p < 0.05$), indicating closer rate-matching for TH preschoolers. Within each sample, SLP-correlations did not differ between testing times, and SLP-correlations for CI time 2 and TH time 1 did not differ.

In the older samples, SLP-correlations were higher for TH than CI participants ($p < 0.001$). Across data sets, CI samples did not differ significantly, and TH samples did not differ, indicating a general pattern of poorer rate-matching among CI users regardless of age. However, the distributions for CI preschoolers were much wider than the other groups: with larger standard deviations (Table II) and interquartile ranges of 0.47 (time 1) and 0.38 (time 2), there was much greater variation in rate-matching among CI preschoolers than other groups, who had interquartile ranges of 0.10–0.16.

3. Normalized speech rate

Figure 1 illustrates the distributions of mean participant normalized speech rates listed in Table II for preschool and older samples, with the shaded area indicating the “target” rate-matching range of normalized rates within 10% of SLP rates, which were set to 0. In the preschool samples, most TH participants fell within this range at time 2, but many TH at time 1 and CI users at both times had slower rates. These latter three groups did not differ in mean normalized rate, and each was significantly slower than TH at time 2 (all $p < 0.05$).

In the older data set, normalized rates were similar between samples, and most participants fell within the “target” range of rates within $\pm 10\%$ of SLP rates, indicating good rate-matching overall. However, mean normalized rates were faster for TH than CI ($p < 0.01$). This effect was driven by teens: mean normalized rates were faster for TH

teens than CI teens and CI children (both $p < 0.05$), but no other age groups differed.

Looking across data sets, it appears that CI preschoolers were delayed in rate-matching performance, behind the TH preschoolers who reached the normalized rates of older CI users (both $p > 0.1$), but by school age, both CI and TH participants were good rate-matchers on average.

4. Distance from SLP rate

Figure 2 illustrates the distributions of mean participant rate-distances, the distances of normalized rates from SLP rates (faster or slower; see also Table II), with a shaded area indicating the “target” rate-matching range of normalized rates within 10% of SLP rates. In the preschool samples, normalized speech rates for CI users at time 1 were significantly farther from (faster or slower than) the SLP model rates than CI at time 2 and than TH at either time (all $p < 0.05$), but these latter three preschool groups did not differ, indicating poorer rate-matching for preschool CI users with less device experience. For older participants, distances from SLP rates were greater for CI users than for TH participants ($p < 0.001$), indicating closer rate-matching for TH participants, about

FIG. 1. Normalized speech rate for (a) preschool samples by testing time and (b) older samples. CI.1 = CI, time 1, etc., black dots = means, black bands = medians, boxes = quartiles 2-3, notches = 95% confidence intervals, horizontal line at 0 = SLP rate, shading = “on-target” range within 10% of SLP rates.

FIG. 2. Distance from SLP rate for (a) preschool samples by testing time and (b) older samples. CI.1 = CI, time 1, etc., black bands = medians, boxes = quartiles 2-3, notches = 95% confidence intervals, shading = “on-target” range within 10% of SLP rates.

half of whom fell in the target rate-matching range, compared to about a quarter of CI users.

Across data sets, delays in rate-matching persisted for CI users through childhood and adolescence. Rate-distances for the older CI users overlapped those for TH preschoolers at both times ($p > 0.1$), which were greater than rate-distances for the older TH sample (both $p < 0.05$).

5. Rate variability

Patterns for rate variability were similar to those for distances from SLP rates. Rates for preschool CI users at time 1 were significantly more variable than CI at time 2 and than TH rates at either time, (all $p < 0.05$), but these latter three groups did not differ, indicating less consistent rate-matching for preschool CI users who had less device experience. In the older samples, normalized rates for CI users were more variable than for TH participants ($p < 0.01$), indicating better rate-matching consistency for the TH sample.

Looking across data sets, it appears that CI preschoolers were delayed in rate-matching consistency. Rate variability for CI preschoolers at each testing time was greater than for each older sample (all $p < 0.05$), but TH preschoolers at both times overlapped both older samples (all $p > 0.1$).

6. Summary

These speech rate measures supported the predictions for research question 1. Raw and normalized speech rates showed that CI users talked more slowly than the TH sample; SLP-correlation and rate-distance showed that CI users were less accurate rate-matchers than TH participants; and rate variability and the wider distributions of rate-matching measures showed that CI users were less consistent rate-matchers than TH participants. Also as predicted, CI preschoolers were especially delayed in rate-matching accuracy (SLP-correlation, rate-distance) and consistency (rate variability) at time 1, but by time 2, their performance was similar to that of TH at time 1, indicating improvement from a large delay at time 1 to a delay of about a year at time 2. In contrast, the increases between testing times in raw and normalized speech rate were similar between the CI

and TH samples, indicating a more consistent 1-year delay for CI users.

B. Research question 2: Relations between speech intelligibility and rate measures

The hypotheses that faster speech rates and better rate-matching would be related to better speech intelligibility, particularly among CI users, were tested with correlations, partial correlations, and comparisons between subgroups of participants. (Significant p -values for t tests are reported in the text; the corresponding t -statistics and degrees of freedom are available from the authors upon request.)

1. Speech intelligibility

Figure 3 shows rank-ordered individual participants' intelligibility scores, with CI users (gray) overlaid on TH participants (white), (a) preschool mean intelligibility plotted separately by testing time, and (b) older perfect-sentence intelligibility. Most TH preschoolers scored above 70% intelligible [time 1 $M = 84\%$, time 2 $M = 90\%$, above the reference line in Fig. 3(a)], but CI users were more variable, with most scoring below 70% (time 1 $M = 49\%$, time 2 $M = 68\%$). CI users at both times were significantly less intelligible than TH preschoolers at both times (all $p < 0.01$), but within each sample, intelligibility improved from time 1 to time 2 (both $p < 0.05$).

Recall that nearly all older TH participants and about two-thirds of older CI users scored above 90% on mean intelligibility (TH: $M = 96\%$, range = 89%–99%; CI: $M = 89\%$, range = 44%–97%, $p < 0.001$; see Montag *et al.*, 2014), and so a stricter method of perfect-sentence intelligibility (the percentage of a participant's sentences which were perfectly transcribed by all listeners) was used to avoid ceiling effects. Similar to the preschool pattern for mean intelligibility, perfect-sentence intelligibility was higher for older TH than

FIG. 3. Rank-ordered individual participants' intelligibility scores, CI (gray) overlaid on TH (white), (a) preschool mean intelligibility by testing time, (b) older perfect-sentence intelligibility. Reference lines at 70% indicate good performance.

TABLE III. Correlations between intelligibility and rate measures.^a

Rate measure	Preschool				Older	
	CI		TH		CI	TH
	Time 1	Time 2	Time 1	Time 2		
	Mean participant intelligibility				Perfect-sentence intelligibility	
Raw rate	0.49*	0.64**	0.19	0.13	0.47***	−0.08
SLP-correlation	0.63***	0.54*	0.48**	0.32	0.47***	0.24
Normalized rate	0.02	0.36	0.12	−0.03	0.41***	−0.04
Rate-distance	−0.52**	−0.52*	−0.62***	−0.47*	−0.49***	−0.28*
Rate variability	−0.60**	−0.65**	−0.69***	−0.28	−0.30*	−0.13
	Sentence intelligibility					
Raw rate	0.24***	0.30***	0.01	0	0.31***	0.01
Normalized rate	0.02	0.21**	0.01	−0.04	0.26***	0
Rate-distance	−0.25***	−0.30***	−0.24***	0.01	−0.28***	−0.07

^aValues are Pearson's r . Alpha-levels corrected within each sample (CI, TH) and intelligibility score (a, b, c) via false discovery rate control. * $p < 0.05$. ** $p < 0.01$. *** $p < 0.001$.

CI participants ($p < 0.001$), and most TH participants scored above 70% [$M = 84\%$, see the reference line in Fig. 3(b)], but most CI users scored below this level ($M = 55\%$).

2. Rate measures and speech intelligibility

Table III lists the correlations between each participant-level rate measure and mean participant intelligibility for preschoolers or perfect-sentence intelligibility for older samples and between each sentence-level rate measure and sentence intelligibility. Preschool participant intelligibility was significantly correlated with all rate measures except normalized rate for CI users at both testing times, and with each rate measure except raw and normalized rate for TH preschoolers at time 1, but only with rate-distance for TH preschoolers at time 2. Older CI users' perfect-sentence intelligibility was significantly correlated with all rate measures for CI users but only with rate-distance for TH participants. (Note that when using mean participant intelligibility for the older samples, the patterns were nearly identical, except that the weak correlations for CI rate variability and TH rate-distance were smaller and not significant.)

Correlations were weaker when relating measures for each sentence rather than each participant, but the overall pattern was similar. Among CI preschoolers, sentence intelligibility was significantly correlated with all three rate measures at time 2, but only raw rate and rate-distance at time 1, and only rate-distance for TH preschoolers at time 1. Older CI users showed significant correlations with all three rate measures, but no rate measure correlated with sentence intelligibility for older TH participants. Thus, speech rate and rate-matching were important factors underlying the intelligibility of CI sentences but not TH sentences (which varied less in intelligibility overall).

3. Contributions of rate-matching beyond speech rate

Given that all rate-matching measures were derived from raw speech rate, it was necessary to determine the unique contributions of rate-matching accuracy and consistency to speech intelligibility above and beyond the influence of raw speech rate alone.

Table IV lists partial correlations controlling for raw speech rate between rate-matching and intelligibility measures. For preschoolers' mean participant intelligibility, significant

TABLE IV. Partial correlations between intelligibility and rate measures controlling for raw speech rate.^a

Rate measure	Preschool				Older	
	CI		TH		CI	TH
	Time 1	Time 2	Time 1	Time 2		
		Mean participant intelligibility			Perfect-sentence intelligibility	
SLP-correlation	0.58**	0.14	0.47**	0.31	0.25	0.26*
Normalized rate	−0.40	−0.21	−0.11	−0.22	−0.09	0.01
Rate-distance	−0.35	0.07	−0.60***	−0.46*	−0.30*	−0.27*
Rate variability	−0.57**	−0.44	−0.73***	−0.29	−0.22	−0.12
		Sentence intelligibility				
Normalized rate	−0.16*	0.05	0.01	−0.04	0.02	−0.03
Rate-distance	−0.21**	−0.21**	−0.24***	0.01	−0.12***	−0.03

^aValues are Pearson's r . * $p < 0.05$. ** $p < 0.01$. *** $p < 0.001$.

correlations were strong with SLP-correlation and rate variability for CI and TH preschoolers at time 1, and with rate-distance for TH preschoolers at both testing times. This pattern suggests that rate-matching accuracy and consistency contributed substantially to speech intelligibility beyond the influence of raw speech rate, particularly at time 1.

Because mean participant intelligibility was high in the older samples, the only significant partial correlation with that measure was weak, with rate-distance for CI users [$r(60) = -0.31, p < 0.05$]. However, significant partial correlations with the stricter perfect-sentence intelligibility measure were weak-to-moderate with rate-distance for both older samples and with SLP-correlation for TH participants, indicating a moderate added contribution of rate-matching accuracy to participant intelligibility after controlling for raw speech rate.

Table IV also lists partial correlations between sentence intelligibility and each sentence-level rate-matching measure for both data sets. For preschoolers, significant correlations were weak with rate-distance for CI sentences at both testing times and TH sentences at time 1. There was also a weak negative correlation with normalized rate for CI sentences at time 1, suggesting that normalized rate was slightly at odds with raw rate for this group. In the older data set, the only significant correlation was weak, with rate-distance for CI users.

4. Speech intelligibility in rate-based subgroups

To compare the intelligibility of good and poor rate-matchers, all CI and TH samples were divided into *normalized-rate subgroups* based on their mean normalized rates: *fast* talkers >10% faster than SLPs, *slow* talkers >10% slower than SLPs, *same-speed* talkers within 10% of SLP rates. Similarly, all CI and TH participants were divided into *rate-distance subgroups* based on their mean rate-distances: *off-target* talkers >10% from SLP rates (faster or slower), *on-target* talkers within 10% of SLP rates. (Note that not all same-speed talkers are on-target; for example, a talker with half his/her sentences at 20% faster and half at 20% slower than SLP rates would have a mean normalized rate of 0 (same-speed) but a mean rate-distance of 20% (off-target).)

Table V displays the number and percentage of participants from each sample assigned to each rate subgroup. Most TH preschoolers were in same-speed normalized-rate subgroups, but CI preschoolers were divided between slow and same-speed, and very few preschoolers were fast talkers. Most preschoolers in both samples were off-target in rate-distance. The combination of same-speed but off-target membership for a speaker indicates inconsistent speech rates (i.e., similar numbers of sentences above and below the target range near SLP rates), while simultaneous slow and off-target membership indicates consistently poorer rate-matching.

Most older participants—a small majority of CI users but a large majority of TH participants—fell in the same-speed subgroup. Most CI users were off-target in rate-distance, while the TH participants were evenly split between off-target and on-target.

TABLE V. Number of participants in each normalized-rate and rate-distance subgroup.^a

Subgroup	Preschool				Older	
	CI		TH		CI	TH
	Year 1	Year 2	Year 1	Year 2		
Normalized rate						
slow	14 (56%)	9 (43%)	10 (33%)	5 (20%)	14 (22%)	1 (2%)
same	10 (40%)	12 (57%)	18 (60%)	20 (80%)	36 (57%)	54 (86%)
fast	1 (4%)	0	2 (7%)	0	13 (21%)	8 (13%)
Rate-distance						
off-target	25 (100%)	17 (81%)	24 (80%)	16 (64%)	48 (76%)	31 (49%)
on-target	0	4 (19%)	6 (20%)	9 (36%)	15 (24%)	32 (51%)

^aValues are *N*s (% of sample). Same/on-target = within 10% of SLP rate; slow/fast/off-target = >10% slower/faster than SLP rate.

In both data sets, more TH than CI participants were in the same-speed and on-target subgroups, indicating more accurate rate-matching among TH participants. These subgroups were also more intelligible than others, and slow and off-target CI subgroups were least intelligible. This pattern is shown in Table VI, which summarizes participant intelligibility (*M*, *SD*) for each rate-based subgroup, with mean participant intelligibility for both data sets and also perfect-sentence intelligibility for the older samples.

a. Normalized-rate subgroups. The preschool normalized-rate subgroups fell into two intelligibility clusters (excluding the one CI user and two TH participants in fast subgroups): slow CI talkers at both testing times and same-speed CI talkers at time 1 did not differ in mean participant intelligibility from each other but were significantly less intelligible than all other preschool subgroups (all $p < 0.05$). The subgroups in this second cluster did not differ except for CI and TH same-speed at time 2 ($p < 0.05$). In short, while TH preschoolers were highly intelligible regardless of rate-matching performance, and CI users with limited device experience (time 1) were much less intelligible regardless of rate-matching performance, CI users with more device experience (time 2) either remained less-intelligible, poor rate-matchers or improved in both domains to match the performance of TH peers.

The older normalized-rate subgroups also fell into two clusters when using mean participant intelligibility, with slow CI talkers significantly less intelligible than all other subgroups (all $p < 0.05$), which did not differ. Using perfect-sentence intelligibility, the older normalized-rate subgroups fell into three clusters (excluding the single slow TH talker): slow CI talkers were significantly less intelligible than all other subgroups (all $p < 0.01$); fast and same-speed CI talkers did not differ but were significantly less intelligible than the TH subgroups (all $p < 0.01$), which did not differ. In short, CI users were less intelligible than TH peers, with slow CI talkers especially low in intelligibility.

Comparing mean participant intelligibility across data sets, the more-intelligible preschool cluster spanned the intelligibility of the older clusters: same-speed CI

TABLE VI. Intelligibility scores for each normalized-rate and rate-distance subgroup.^a

Subgroup	Mean participant intelligibility						Perfect-sentence intelligibility	
	Preschool				Older		Older	
	CI		TH					
	Time 1	Time 2	Time 1	Time 2	CI	TH	CI	TH
Normalized rate								
slow	52 (24)	54 (32)	82 (19)	90 (9)	79 (16)	[93 (na)]	37 (22)	[72 (na)]
same	42 (31)	78 (19)	86 (8)	90 (5)	92 (5)	96 (2)	60 (16)	85 (6)
fast	[83 (na)]		[79 (24)]		90 (9)	95 (2)	59 (18)	81 (6)
Rate-distance								
off-target	49 (28)	62 (27)	82 (14)	89 (6)	87 (12)	95 (2)	51 (21)	82 (7)
on-target		93 (5)	93 (5)	93 (4)	95 (2)	96 (2)	68 (8)	86 (5)

^aValues are means (*SDs*) % intelligible. Same/on-target: within 10% of SLP rate; slow/fast/off-target: >10% slower/faster than SLP rate. Brackets: $N < 3$ participants, not discussed in text.

preschoolers at time 2 and both TH subgroups at time 1 reached the moderately high intelligibility of older slow CI talkers, while TH preschool subgroups at time 2 reached the very high intelligibility of the older fast and same-speed subgroups (all $p > 0.05$).

b. Rate-distance subgroups. The preschool rate-distance subgroups (Table VI) fell into three clusters. Off-target CI subgroups did not differ in intelligibility between testing times but were less intelligible than all other subgroups (all $p < 0.01$). Off-target TH at time 1 differed from all other subgroups with moderately high intelligibility (all $p < 0.05$). All on-target subgroups and off-target TH at time 2 did not differ with the highest intelligibility.

The older rate-distance subgroups fell into three clusters based on mean participant intelligibility, with off-target CI users lower than all other subgroups (all $p < 0.05$), on-target TH higher than all others (all $p < 0.05$), and on-target CI and off-target TH equally close behind. Using perfect-sentence intelligibility, all older subgroups differed in intelligibility: TH participants were more intelligible than CI users, and within each CI or TH sample, on-target talkers were more intelligible than off-target talkers (all $p < 0.05$).

Comparing mean participant intelligibility across data sets, off-target TH preschoolers overlapped the moderately high intelligibility of older off-target CI users, and on-target TH and CI preschoolers overlapped the high intelligibility of older on-target CI users and both older TH subgroups (all $p > 0.1$).

5. Summary

Predictions for research question 2 were supported. Most rate measures were correlated with speech intelligibility, and they were more strongly correlated in the CI than TH samples. Most rate-matching measures contributed to intelligibility beyond the effect of raw speech rate, with rate-distance proving to be a particularly useful predictor. Slower CI talker subgroups and off-target rate-matchers were the least intelligible, indicating that better rate-matching was

related to more intelligible speech. Slow and off-target CI preschool talkers did not improve in intelligibility between testing times, but same-speed CI preschoolers improved substantially from time 1 to time 2. Across data sets, older samples showed better rate-matching performance than preschoolers, consistent with a developmental trajectory that reached good performance early in school ages, as predicted.

IV. DISCUSSION

Predictions for both research questions were supported. CI users from preschool through young adulthood had slower speech rates, less accurate and less consistent rate-matching, and poorer speech intelligibility than TH peers. Speech rate and rate-matching measures were correlated with speech intelligibility in both CI and TH data sets; i.e., faster talkers and better rate-matchers were more intelligible. Rate-matching and intelligibility improved from one year to the next during preschool, with CI users delayed in performance by about a year. By school-age, rate-matching and intelligibility were high overall, but delays still persisted for many CI users compared to TH peers.

A. Implications and clinical relevance

These results demonstrate that speech rate and rate-matching contribute to speech intelligibility, particularly in prelingually deaf CI users, who show delays and wide individual differences in rate-matching, intelligibility, and other speech-language outcomes. The importance of speech rate-matching to both intelligibility and convergence or accommodation skills forms a new direction in CI research with clinical implications. CI users may benefit from novel interventions that target the appropriate modulation of speech rate and rate-matching, such as rate control methods used in treatments of dysarthria (Blanchet and Snyder, 2010). Following the assumption that the local adaptation skills involved in speech-rate matching also underlie rhythmic convergence skills at the discourse level, greater attention to speech rate could benefit linguistic perceptions of CI users in

multiple ways. Speech rate patterns that are expected by interlocutors in a given communicative setting affect not only speech intelligibility and cognitive processing but also interpersonal rapport and others' perceptions of the CI user's competence, personality, or likeability—psycho-social evaluations that may in turn affect friendships, self-image, and even employment opportunities (Borrie and Liss, 2014; Most, 2010). In other words, improving speech rate skills may impact CI users' quality of life directly as well as indirectly through their effects on speech intelligibility.

B. Limitations and future directions

A limitation of the current study is its *post hoc* correlational nature. While the underpinnings of speech rate control or its relation to speech intelligibility cannot be addressed with the present methods, speech rate-matching can be examined more systematically. Follow-up studies are currently underway to experimentally manipulate the speech rates of presented material in eliciting speech rate-matching in repetitions, read material, and open responses. Using pre-recorded stimuli will control for another limitation: the potential confound of inconsistent presentation rates across participants. Previous work has shown that adults modulate their speech rate in relation to a child's age (Broen, 1972), and adults converge toward their interlocutors on a variety of acoustic measures, including speech rate (see Pardo 2013), even when encountering the exceptionally fast or slow rates of dysarthric speech (Borrie and Liss, 2014). By the time the speech intelligibility tests were administered, the SLPs had already interacted with the children for about an hour, so they may have already modulated their sentence presentation rates to more closely match each child's natural rate. However, differences in rate-matching to the SLP's model rates remained between samples and participants, even after normalizing for SLP presentation rate. This finding suggests that the skill responsible for rapid speech rate adaptation may not operate optimally in all CI users, and it may therefore be an important source of unexplained variance and individual differences routinely found among CI users in previous work. The rate-matching skill may be an underlying contributor to speech accommodation and convergence behaviors in more natural conversational settings. Experimental designs that elicit naturalistic spontaneous speech while controlling presentation speech rate can address the limitations of using a sentence repetition task, which is not encountered in everyday communication. However, in clinical settings, sentence-repetition tasks are easy to administer and may be used to model and practice communication fluency and intelligibility.

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APPENDIX

See Table VII.

TABLE VII. Results of Welch's *t* tests discussed for speech rate measures in Research Question 1 that showed significant differences between participant groups.^a

Samples	Groups	df	t
SLP raw rate			
Preschool	CI < TH	69.24	2.29*
Older	CI < TH	119.36	5.59***
Across sets	preschool < older	215.83	−16.40***
Raw rate			
Preschool	CI < TH	86.30	−3.57***
	CI.1 < TH.2	46.50	−4.20***
Older	CI < TH	106.55	−5.40***
Across sets	preschool < older	140.91	−13.23***
SLP-correlation			
Preschool	CI.1 < TH.1	36.35	−3.15**
	CI.2 < TH.2	35.34	−2.08*
Older	CI < TH	84.43	−4.45***
Normalized rate			
Preschool	CI.1 < TH.2	47.23	−3.19**
	CI.2 < TH.2	40.61	−2.26*
	TH.1 < TH.2	51.71	−2.02*
Older	CI < TH	87.93	−2.87**
	CI teen < TH teen	32.36	−2.10*
	CI child < TH teen	31.17	−2.43*
Rate-distance			
Preschool	CI.1 > CI.2	43.73	2.45*
	CI.1 > TH.1	41.97	3.09**
	CI.1 > TH.2	38.73	4.15***
Older	CI > TH	85.99	3.95***
Across sets	TH.1 > older TH	38.26	2.99**
	TH.2 > older TH	33.25	2.13*
Rate variability			
Preschool	CI.1 > CI.2	31.03	2.51*
	CI.1 > TH.1	32.04	2.40*
	CI.1 > TH.2	31.80	3.20**
Older	CI > TH	119.04	2.85**
Across sets	CI.1 > older CI	25.95	2.84**
	CI.1 > older TH	25.29	3.59**
	CI.2 > older CI	21.87	2.86**
	CI.2 > older TH	21.23	3.65**

^aOnly comparisons discussed in the text are shown. df = degrees of freedom; t = *t*-statistic; CI.1 = CI time 1, etc.; < and > compare means between groups. **p* < 0.05. ***p* < 0.01. ****p* < 0.001.

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