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Research Note

Phonological Awareness and Working Memory in Mandarin-Speaking Preschool-Aged Children With Cochlear Implants

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ABSTRACT

Purpose: Cochlear implants (CIs) provide significant benefits for profoundly deaf children in their language and cognitive development. However, it remains unclear whether Mandarin-speaking young children with early implantation can develop age-equivalent phonological awareness (PA) skill and working memory (WM) capacity as their normal hearing (NH) peers. The aim of this study was to investigate PA and WM in preschool-aged children with or without hearing loss and to examine the relationship between the two basic skills.
Method: The data were collected from 16 Mandarin-speaking preschoolers with CIs and 16 age-matched children with NH. All preschool participants were instructed to complete four phonological detection tasks and four digit span tasks. Linear mixed-effects modeling was performed to evaluate PA and WM performances between two groups across different tasks.
Results: CI preschoolers showed comparable performances on par with NH controls in phonological detections and visual digit spans. In addition, Pearson correlation analysis revealed a positive relationship between phonological detections and auditory digit spans in preschool-aged children with CIs.
Conclusion: With early implantation, the congenitally deaf children were capable of developing age-appropriate PA skill and WM capacity, which have practical implications for aural rehabilitation in this special pediatric population.

As an essential linguistic skill, phonological awareness (PA) plays a pivotal role in literacy success across typologically different languages (Anthony & Francis, 2005). Recent meta-analyses revealed that PA is a significant predictor of reading ability in typically developing children with normal hearing (NH) of both alphabetic (e.g., English and Spanish) and logographic (e.g., Chinese) languages (Míguez-Álvarez et al., 2021; Ruan et al., 2018). According to several independent studies, PA demonstrates causal connections with spoken language acquisition, vocabulary knowledge, and reading abilities in congenitally deaf children with cochlear implants (CIs; Jung & Houston, 2020; Lee, 2020; Lund, 2020). Poor PA could pose serious challenges to the typical development of speech and language. Therefore, the evaluation of PA skill with the goal of intervention in need is a critical component in the rehabilitation programs for children with CIs.

In contrast with the existing literature on PA for children with CIs in alphabetic languages (see Ingvalson et al., 2020, for a review), the number of studies on this topic in Chinese children is rather limited (but see L. Zhang et al., 2021). However, findings of pediatric CI users from alphabetic languages cannot be simply generalized to their counterparts from nonalphabetic languages as Chinese. It is well documented that the development of PA skill is closely related to the orthographic transparency of language systems (Ziegler & Goswami, 2005). Unlike alphabetic languages,

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Chinese does not abide by the "alphabetic principle," and the sound–symbol mapping in written Chinese is fairly opaque (Perfetti et al., 2005). In addition, the use of syllable-level lexical tones represents an integral feature of Chinese phonological information, which is absent from most Indo-European languages. Previous literature has shown that sensitivity to tone could facilitate reading in typically developing Chinese children (Shu et al., 2008). Moreover, given that the tasks of PA tap into a variety of cognitive skills (Anthony & Francis, 2005), this exploratory study was designed to evaluate PA and its relationship with the basic cognitive capacity of working memory (WM) in Chinese preschoolers with CIs.

PA

According to Gillon (2004), PA refers to a child's ability to reflect on the phonological structure of words independent of their meanings. As metalinguistic knowledge, PA underlies children's developing performance to recognize, discriminate, and manipulate different units of spoken language. On the basis of phonological units, PA can further be divided into syllable awareness, rime awareness, onset awareness, phoneme awareness, and tone awareness for tonal languages (Shu et al., 2008).

PA depends on the refinement of phonological representations of spoken language during childhood. According to the lexical restructuring hypothesis, phonological representations are initially formed as relatively holistic, which gradually become more segmental in shape along with children's increasing number of lexical entries (Metsala, 1997, 1999). It follows that the basic developmental trajectory of PA in typically developing children with NH generally begins with awareness of larger units as word and syllable, which is followed sequentially by awareness of smaller units as rime and onset (Cupples, 2001). A recent study indicated that Mandarin-speaking children with NH obtained ceiling level in syllable awareness by Grade 2, whereas their onset and rime awareness were still under development across grades (Lin et al., 2020). With regard to phonemic awareness, Mandarin-speaking school-aged children showed fairly limited level far from saturation even at Grade 5 (Yeh et al., 2015). The development of phonological representations is highly dependent on a child's auditory experience and hearing acuity. Phonological representations are shaped and stored in the mental lexicon, which are progressively tuned by continuous exposure to the sound patterns and structures of the spoken language in the ambient environment. Children with congenital deafness persistently struggle with forming phonological representations with specific issues in phonological sensitivity and phonological memory (Ingvalson et al., 2020). Moreover, the stability and maturity of phonological representations are closely related to the PA skill, because the stored representations in memory contain the phonological structure of specific words and the constituent segments. Therefore, weakness in the establishment of strong phonological representations may contribute to deficits in the development of PA (Preston & Edwards, 2010). Simply put, children with hearing impairment may encounter great challenges in learning PA skill due to their poor phonological representations as a result of long-term diminished auditory experience or auditory deprivation. Further investigations are warranted to delve into whether Mandarin-speaking deaf children could reap the benefits of the CI use and share a developmental framework of PA similar to their NH peers.

The advent of the CI device as a treatment for prelingual deafness affords an opportunity to refine phonological representations and acquire the spoken language. For instance, English-speaking preschool-aged CI recipients were shown to be capable of developing PA skills (Ambrose et al., 2012; James et al., 2005). Tse and So (2012) also reported that Cantonese-speaking children with CIs showed the potential to achieve age-appropriate abilities of syllable awareness, rime awareness, and onset awareness like their NH peers. However, the contemporary CI devices provide degraded spectral–temporal information, which might constrain the rehabilitative progress in children with CIs and contribute to great individual variability in pediatric CI users' auditory, linguistic, and cognitive performances (see van Wieringen & Wouters, 2015, for a review). A body of literature has documented some demographic factors (e.g., chronological age, implantation age, and duration of CI use) accounting for the heterogeneity of CI outcomes in this clinical population (e.g., Dunn et al., 2014; Hong et al., 2019; Johnson & Goswami, 2010; Lee, 2020; Moreno-Torres et al., 2016). A consistent finding is that children implanted earlier show higher possibilities to build phonological representations and develop phonological processing skills on par with NH age-mates. Given that the CI device is relatively poor in coding pitch information in speech, it remains to be tested whether the Mandarin Chinese pediatric recipients who receive CIs at an earlier age and with relatively longer CI accommodation can develop age-equivalent PA skill.

A wide range of tasks can be adopted to evaluate a child's PA skill, including blending single sounds together, deleting a single sound from words, segmenting words into constituent sounds, and detecting whether words share some sounds in common. Among these tasks, phonological detection requires forced choices for measuring PA skill, which may have lower ecological validity than tasks with open-ended responses. The key caveat for obtaining a reliable estimate lies in matching the difficulty of a particular task and the level of PA development of the child participant (Anthony & Francis, 2005). The forced-choice paradigm is considered to be most appropriate in PA evaluation for very young children as the task instructions tend to be much easier for them to follow (Shu et al., 2008). As some children may show problems in speech production, such speech deficits would potentially confound the PA results when open-ended oral responses are required. Thus, we chose to examine the four levels of PA skill in Mandarin-speaking preschoolers with or without NH using the forced-choice tasks of syllable detection, rime detection, onset detection, and tone detection.

WM

WM is defined as the cognitive ability to temporarily store and simultaneously manipulate information for further processing of higher level cognitive activity (Baddeley, 2003). It has been demonstrated that speech perception is closely associated with phonological coding of the auditory input in WM (Gathercole et al., 2004). Specifically, WM bridges the auditory input of speech waveforms and the listener's phonological and lexical representations of words stored in long-term memory (Pisoni et al., 2011). Therefore, WM provides a platform for language processing. Digit span tasks, including forward digit span and backward digit span, are commonly used to evaluate an individual's WM capacity. Forward digit span requires the listener to repeat the digits in the same order as presented, whereas backward digit span requires the listener to reproduce the digits in the reversed order as presented. Conventionally, both tasks typically involve auditory presentation and verbal responses. Span is determined as the number of digits for which one can recall the digit strings. Therefore, these tasks are feasible to assess how well the participants can maintain immediate verbal memory (i.e., the digits) in mind for the ongoing processing demands.

A myriad of studies have documented significant delays of verbal WM development in pediatric CI users relative to NH peers with the implementation of the conventional digit span tasks (e.g., AuBuchon et al., 2015; Burkholder & Pisoni, 2003; Fagan et al., 2007; Pisoni & Geers, 2000; Pisoni et al., 2011). In addition, some more complex tasks also revealed the diminished verbal WM for children with CIs. For example, Nittrouer et al. (2013, 2017) adopted a serial recall task that manipulated the rhyming congruency (i.e., rhyming and nonrhyming conditions) of to-be-remembered words to disentangle the two components of verbal WM (i.e., storage and processing). The premise of the experimental design was that storage and processing could be indexed by child participants' recall accuracy and recall response speed, respectively. Their longitudinal study showed deficits of WM in children with CIs lay in problems of storage but not processing at the second-grade test session (Nittrouer et al., 2013), whereas WM deficits related to both storage and processing at the fourth-grade test session (Nittrouer et al., 2017). It should be noted that degraded auditory input and constrained productive performance could confound the interpretation of potential deficits in WM capacity and spoken language skills in pediatric CI population. To avoid the possibility of poor auditory resolution and vocal mediation, AuBuchon et al. (2015) implemented the digit span tasks using different presentation modalities (i.e., auditory and visual) and response modes (i.e., verbal and nonverbal) in a group of adolescents with relatively late cochlear implantation (within 7 years of age). Their results suggested that CI users' WM deficits persisted regardless of presentation modality or response mode of the tasks (AuBuchon et al., 2015, 2019). The development of executive function as verbal WM begins early in childhood by 2 years of age (Cuevas & Bell, 2014). Further investigations are needed to probe whether early-implanted children (within 2 years of age) could exhibit WM performance comparable with NH peers in digit span tasks with visual presentation and nonverbal response.

It is proposed that basic neurocognitive functioning may underlie the large individual differences and variabilities among CI individuals in speech and language outcomes (see Kronenberger & Pisoni, 2020; Pisoni et al., 2016, for reviews). In particular, WM capacity shows most evidently reciprocal relationships with pediatric CI users' performances of speech and language (Kronenberger & Pisoni, 2018). Performances of verbal digit span tasks in children with CIs during childhood are correlated with their speech and language outcomes in adolescence after 10 more years of CI experience (Pisoni et al., 2011). Higher level language skills of CI children as morphosyntactic ability could also be predicted by their verbal WM performances (de Hoog et al., 2016). Moreover, a recent longitudinal investigation confirmed the significant role of WM in predicting later developed spoken language skills in preschool-aged children with CIs (Kronenberger et al., 2020). Compelling evidence of the causal influence of verbal WM on speech and language outcomes also comes from auditory cognitive training research (Ingvalson et al., 2014; Kronenberger et al., 2011; Mishra & Boddupally, 2018), in which speech and language improvements were shown in pediatric CI users receiving auditory WM training (e.g., forward and backward digit span training). These prior studies open the prospect of pursuing the question of whether WM capacity associates with variabilities in basic-level metalinguistic skills as PA and the relationship between these two fundamental aspects has rarely been investigated.

This Study

The objective of this study was to compare the performance of Mandarin-speaking preschoolers with CIs with that of their NH peers in terms of PA skill and WM capacity. The main research questions of this study were as follows: (a) Do preschool-aged children with early implantation show PA skill on par with their age-mates? (b) Can these clinical children be afforded the opportunity to develop age-equivalent WM capacity? (c) Is there any significant relationship between PA and WM performances in the preschoolers with CIs? In accordance with prior work (Kronenberger & Pisoni, 2018; Romano et al., 2021; Tse & So, 2012), our running hypotheses were as follows: (a) Mandarin-speaking children with CIs can show comparable overall performance with their peers in phonological detection with the benefit of early implantation age and relatively longer CI accommodation. (b) Although deficits may persist in verbal recall of digit span using auditory presentation, the preschoolers with CIs can show age-equivalent WM performance in digit span tasks with visual presentation and nonverbal response. (c) Because verbal WM shows reciprocal association with speech and language outcomes in deaf children with CIs (Kronenberger & Pisoni, 2018), there can be a significant positive relationship between the CI preschoolers' PA and WM performances.

Method

Participants

Sixteen native Mandarin-speaking children (seven boys and nine girls) aged from 4.7 to 6.97 years with prelingual bilateral deafness were recruited from the Shanghai Rehabilitation Center of the Deaf Children. All the preschool-aged children were identified with severe-to-profound hearing loss shortly after birth via newborn hearing screening. They were implanted unilaterally before 2 years of age and had a duration of CI use for more than 3 years. Seven of the CI children were fitted with MED-EL OPUS (speech strategy: FS4-p [Fine Structure Processing]), six of them had Cochlear Nucleus (speech strategy: ACE [Advanced Combination Encoder]), and three had Advanced Bionics (speech strategy: HiRes Optima [High Resolution Optima]). Fourteen of them also used a contralateral hearing aid (HA) in daily settings. Apart from hearing impairments, they had no history of psychiatric disorders or brain injuries according to clinical reports. The Hiskey–Nebraska Test of Learning Aptitude was adopted to screen the child participants' nonverbal intelligence (Hiskey, 1966). All child subjects with CIs obtained scores significantly higher than the passing score of 84, indicating normal nonverbal intelligence for all clinical child participants (Yang et al., 2011). Their demographic information is shown in Table 1.

In addition, 16 typically developing children with NH were recruited from a local kindergarten as controls. The control group matched the CI group in terms of chronological age, gender, and nonverbal intelligence. Table 2 summarizes the demographic characteristics of the two groups. None of the child participants received formal literacy instructions on phonological coding in kindergartens. Approval of the study was granted by the ethics committee for research involving human subjects at Shanghai Jiao Tong University. Informed consent was received from the caregiver of each preschool-aged subject.

Table 1. Demographic information of the child participants with cochlear implants (CIs).

Subject (sex)	CA (yrs)	CI (ear)	Speech strategy	HA	Hearing status	Age at CI (yrs)	CI duration (yrs)	Age at HA (yrs)	H-NTLA
S1 (M)	6.1	OPUS 2 (R)	FS4-p	Widex C3-FS	Bimodal	1.7	4.4	1.5	109
S2 (M)	4.7	Nucleus 6 (L)	ACE	Phonak Q90 SP	Bimodal	1.7	3.	2.6	110
S3 (M)	5.9	Nucleus 5 (R)	ACE	Phonak Naída S IX UP	Bimodal	1	4.9	1.4	106
S4 (M)	5.1	OPUS 2 (R)	FS4-p	Phonak Naída S IX UP	Bimodal	1	4.1	0.6	103
S5 (M)	5.8	Nucleus 6 (L)	ACE	ReSound AL777	Bimodal	1.9	3.8	3.6	108
S6 (M)	6	Naída (R)	HiRes Optima	Phonak Naída S IX UP	Bimodal	1.8	4.2	2.2	124
S7 (M)	5.1	Nucleus 5 (R)	ACE	Phonak Naída S IX UP	Bimodal	1.4	3.7	2.6	124
S8 (M)	5.4	OPUS 2 (R)	FS4-p	Widex C4-FS	Bimodal	0.9	4.5	0.6	104
S9 (F)	7	OPUS 2 (R)	FS4-p	Phonak Naída S IX UP	Bimodal	1.4	5.6	1.4	105
S10 (F)	4.9	OPUS 2 (R)	FS4-p	Phonak Bolero Q50 SP	Bimodal	0.9	4	0.6	117
S11 (F)	5	OPUS 2 (R)	FS4-p		CI alone	1.9	3.1		103
S12 (F)	5.8	Nucleus 6 (R)	ACE	Phonak Naída S IX UP	Bimodal	2	3.8	3.7	106
S13 (F)	5.8	Naída (R)	HiRes Optima	Phonak Naída S V SP	Bimodal	1	4.7	1.1	114
S14 (F)	5.1	Nucleus 5 (R)	ACE		CI alone	1.2	3.9		96
S15 (F)	5.7	OPUS 2 (R)	FS4-p	Phonak Q90 UP	Bimodal	2	3.7	1.2	106
S16 (F)	6.2	Neptune (R)	HiRes Optima	Phonak Q70 SP	Bimodal	1	5.2	2.5	109

Note. CA = chronological age; yrs = years; HA = hearing aid; H-NTLA = Hiskey–Nebraska Test of Learning Aptitude; M = male; R = right; FS4-p = Fine Structure Processing; L = left; ACE = Advanced Combination Encoder; HiRes Optima = High Resolution Optima; F = female.

Table 2. Child participants' demographic characteristics and the available *p* value of independent-samples *t* tests between the two groups.

Characteristics	CI children	NH control	*p* value
H-NTLA (*SD*)	109 (7.79)	111 (6.14)	.36
Chronological age (*SD*)	5.59 yrs (0.60)	5.55 yrs (0.61)	.83
Age at CI (*SD*)	1.43 yrs (0.44)		
CI duration (*SD*)	4.16 yrs (0.71)		

Note. CI = cochlear implant; NH = normal hearing; H-NTLA = Hiskey–Nebraska Test of Learning Aptitude; yrs = years.

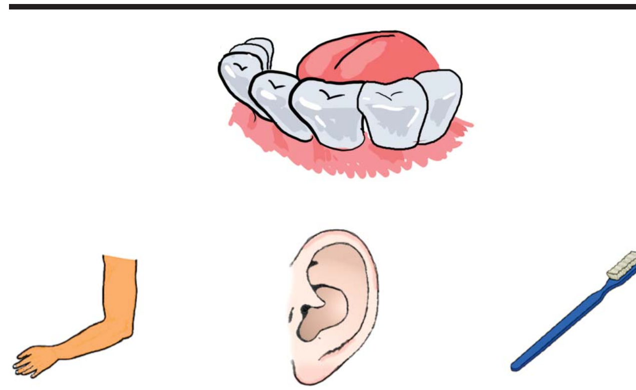
Materials and Procedure

All participants were tested individually inside a quiet room with the background noise level controlled below 35 dBA. Two measures, phonological detection and digit span tasks, were presented to the preschoolers in a random order. Each child was instructed to complete four phonological detection tasks that were modified on the basis of Shu et al. (2008) and four digit span tasks that were adopted in AuBuchon et al. (2015). All chosen tasks had been proven feasible to assess PA skill and WM capacity among kindergarten-aged children. These tasks were implemented with the E-Prime 2.0 program (Psychology Software Tools Inc.) on a Windows-based laptop. All auditory materials were presented to the child participants in the free field via a loudspeaker (JBL CM220), which was placed approximately 1.2 m from the listener. The whole session lasted 30–40 min.

Four phonological detection tasks (i.e., syllable detection, rime detection, onset detection, and tone detection) were employed to measure the child participants' PA skill at different levels. Experimental design of the tasks was the same as Shu et al.'s (2008) study, except that we modified the original two-alternative forced-choice response paradigms into a three-alternative forced-choice one to increase reliability estimates. This subtle modification has been proven feasible in our prior study (Chen et al., 2016). These previous works provided the verification of the four phonological detection tasks in assessing the PA skills in Mandarin-speaking children with NH, despite that this study may represent the first foray into extending these tasks into children with CIs. Disyllabic words were involved as test materials for the syllable detection task, whereas monosyllabic words were used for the other three tasks. Each task consisted of two practice trials and 12 experimental trials with an audiovisual presentation. In all four tasks, children were initially instructed to listen carefully to the target word 3 times. Thereafter, they were required to select which one sounded most similar to the target word from three options. For example, in the syllable detection task, the target "ya2chi3" (tooth) was orally presented to the child participants 3 times with its accompanying representative picture, followed by three optional words "ge1bo" (arm), "er3duo" (ear), and "ya2shua1" (toothbrush), accompanied by their respective pictures (see Figure 1). The examples of rime detection, onset detection, and tone detection can be found in Appendixes A–C. Children were required to select the orally presented word that sounded most similar to the target ("ya2chi3") from the three choices ("ge1bo," "er3duo," and "ya2shua1"). The correct answer, in this case, is "ya2shua1," because it shares the syllable "ya2" with the target. The participants scored 1 point if their answer was correct.

The four digit span tasks were auditory digit span–forward (ADS-F), auditory digit span–backward (ADS-B), computerized digit span–forward (CDS-F), and computerized digit span–backward (CDS-B), which were used to investigate WM capacity of the child participants. In all tasks, participants began with two digits as the initial size. Two lists of digits were prepared for each size level. The next size level, by increasing one digit on the current size, would not present unless the participant correctly responded at least one list of the current size. In other words, the digit span tasks would terminate if the participant failed to reproduce both lists of the current size. Two practice items were provided

Figure 1. An example of the syllable detection task. The upper picture indicates the target sound "ya2chi3," whereas the three lower pictures indicate three options: "ge1bo," "er3duo," and "ya2shua1," respectively.



before the experimental lists for each task to ensure that all participants could follow the requirements of the task. In the two ADS tasks, the audio-recorded digit lists were presented at a rate of one digit per second via a high-quality loudspeaker. The child participants were required to repeat the digit lists orally in either forward (ADS-F) or backward (ADS-B) order. The two CDS tasks were developed to match the ADS ones while using the visual presentation of the lists and manual touching of the responses. The serial digits were visually presented at one digit per minute on a computer screen, and the child participants were instructed to touch the digits out on a touch screen in either forward (CDS-F) or backward (CDS-B) order. The touching responses were performed after the offset of the final digit of the list via a 3 × 3 grid (1 in the upper left to 9 in the lower right) on the touch screen of an iPhone 6s Plus. In all four digit span tasks, each child participant's trial-by-trial digit recall responses were logged by a single experimenter instantly on an answer sheet under the supervision of a certified speech-language pathologist. The participants received 1 point whenever they achieved a correct response.

Data Analyses

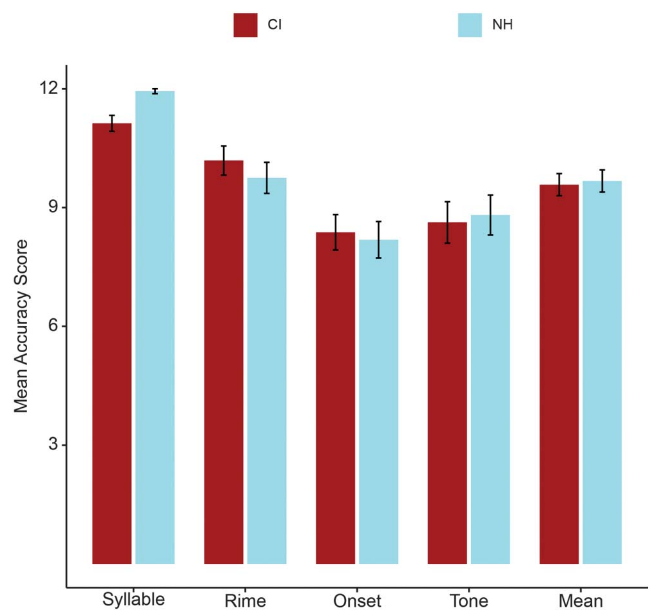
Statistical analyses were performed with linear mixed-effects modeling using lme4 package (Bates et al., 2015) in R Version 3.6.1. The random effects were constructed with by-subject random intercepts and maximal random slopes. The fixed effects were group (CI children and NH control), level (syllable, rime, onset, and tone), and their interactions in PA results, whereas group (CI children and NH control), type (auditory and visual), task (forward and backward), and all possible interactions in WM responses. The packages of lmerTest (Kuznetsova et al., 2017) and lsmeans (Lenth, 2016) were adopted to estimate *p* values and pairwise comparisons, respectively. Moreover, the Pearson correlation was employed to analyze the relationship between the PA skill and the WM capacity for preschool-aged children with CIs.

Results

Phonological Detection Results

The group mean accuracy scores of phonological detection in different tasks are shown in Figure 2 for CI preschoolers and NH controls. The mixed-effects model showed a significant main effect of level, $\chi^2(3) = 77.83$, $p < .001$. Nevertheless, both the main effect of group, $\chi^2(1) = 0.06$, $p = .81$, and the interaction effect of group

Figure 2. Mean accuracy scores of phonological detection in the cochlear implant (CI) and normal hearing (NH) groups as a function of different tasks.



and level, $\chi^2(3) = 4.26$, $p = .23$, failed to approach significance. On the basis of the best fit model, lmer(Score ~ Level + [1 | Subject], REML = FALSE), post hoc pairwise comparisons were conducted via lsmeans package (Lenth, 2016). Planned pairwise comparison with false discovery rate correction (Benjamini & Yekutieli, 2001) indicated that the performance of syllable-level detection was significantly better than that of rime, $\beta = 1.56$, $SE = 0.33$, $t(99) = 4.72$, $p < .001$; onset, $\beta = 3.25$, $SE = 0.33$, $t(99) = 9.81$, $p < .001$; and tone-level detections, $\beta = 2.81$, $SE = 0.33$, $t(99) = 8.49$, $p < .001$. Meanwhile, rime awareness was significantly better than onset, $\beta = 1.69$, $SE = 0.33$, $t(99) = 5.09$, $p < .001$, and tone, $\beta = 1.25$, $SE = 0.33$, $t(99) = 3.77$, $p = .002$. However, the difference between performances of onset and tone was insignificant, $\beta = -0.44$, $SE = 0.33$, $t(99) = -1.32$, $p = .19$.

Digit Span Results

Figure 3 displays the mean accuracy scores of the four digit span tasks for both groups. Statistically, the best fit model formula for WM analysis was as follows: lmer(Score ~ Group × Type × Task + [1 + Task | Subject], REML = FALSE). The constructed mixed-effects modeling showed significant main effects of type, $\chi^2(1) = 23.58$, $p < .001$, and task, $\chi^2(1) = 61.33$, $p < .001$. In general, auditory presentation types obtained significantly higher scores over the visual counterparts, $\beta = 0.98$, $SE = 0.20$, $t(68) = 5.05$, $p < .001$, and the forward tasks were

Figure 3. Mean accuracy scores of four digit span tasks in the two groups. CI = cochlear implant group; NH = normal-hearing group; ADS-F = auditory digit span–forward ADS-B = auditory digit span–backward CDS-F = computerized digit span–forward CDS-B = computerized digit span–backward. Statistical significances are provided: One asterisk represents $p < .05$ and ns represents $p > .05$.

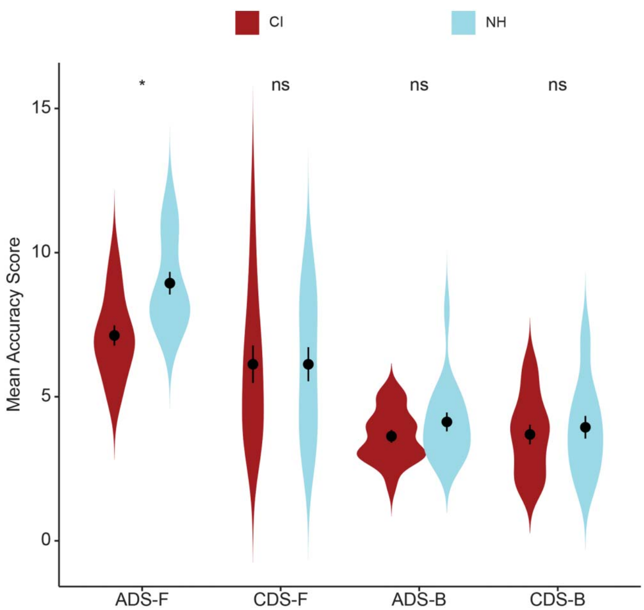
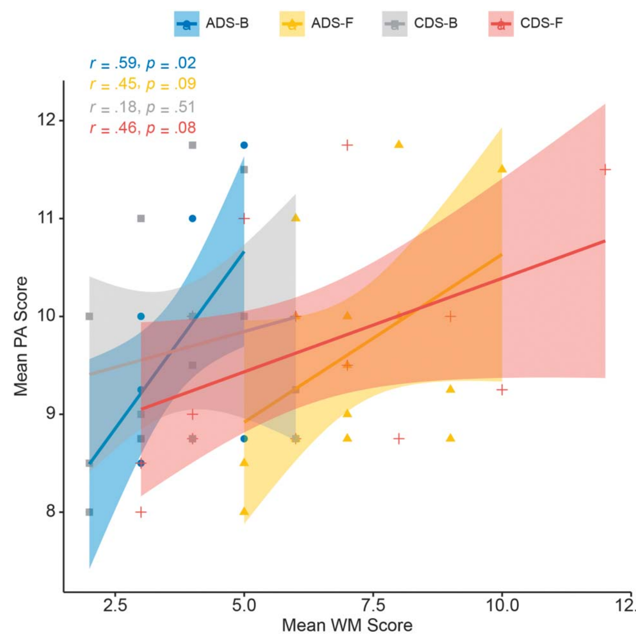


Figure 4. Relationship between phonological awareness (PA) skill and working memory (WM) capacity detected by the four digit span tasks for the cochlear implant children. ADS-F = auditory digit span–forward ADS-B = auditory digit span–backward CDS-F = computerized digit span–forward CDS-B = computerized digit span–backward. The gray shades indicate 95% confidence interval.



significantly easier to reproduce than the backward ones, β = 3.23, *SE* = 0.25, $t(34) = 13.19$, $p < .001$. Moreover, the interaction effects of group and type, $\chi^2(1) = 7.09$, $p = .008$; type and task, $\chi^2(1) = 20.98$, $p < .001$; and group, type, and task, $\chi^2(1) = 4.15$, $p = .04$, were also found significant. Further models were constructed to unpack the three-way interaction effect. The main effect of group was only significant in the ADS-F task (i.e., auditory type and forward task), with CI preschoolers performing significantly worse than NH peers, β = −1.81, *SE* = 0.70, $t(47) = -2.58$, $p = .01$. In addition, the main effect of type was significant only in forward tasks, with a better performance in auditory type (i.e., ADS-F) than in visual type (i.e., CDS-F) for both the CI group, β = 1.00, *SE* = 0.39, $t(68) = 2.57$, $p = .01$, and the NH group, β = 2.81, *SE* = 0.39, $t(68) = 7.22$, $p < .001$. However, the significant main effect of task was displayed in both presentation types for both participant groups.

Correlation Results

The relationships between the PA skill reflected by the average scores across four detection tasks and the WM capacity in four digit spans are collectively arranged in Figure 4 for all recruited children with CIs. The CI participants' PA skill, as a whole, tended to have a positive correlation with their WM capacity, especially with the backward digit spans for the ADS-B ($r = .59$, $p = .02$). Meanwhile, a similar (but not statistically significant) trend was observed between the mean PA scores and the forward digit spans revealed by the ADS-F ($r = .45$, $p = .09$) and the CDS-F ($r = .46$, $p = .08$).

Discussion

This study investigated the performances of phonological detection and digit span tasks in Mandarin-speaking preschoolers with CIs and compared to those in NH age-mates. In addition, the relationship between the two fundamental core skills was evaluated among children with CIs. The results indicated that young children who received contemporary CI devices at a relatively earlier age (within 2 years of age) have the potential to develop comparatively age-appropriate basic phonological and cognitive skills as their NH peers. Moreover, the positive correlation between phonological detections and digit spans suggested that the PA outcomes could potentially explain the differences and variabilities of WM capacity among the kindergarten-aged children with CIs.

The results largely support our hypothesis. Consistent with the lexical restructuring hypothesis (Metsala, 1997; Walley et al., 2003), the CI children and NH controls showed comparable patterns in PA performance with significantly better detection of syllable and rime over onset and tone. Despite auditory deprivation in early life, preschoolers with CIs in our study were able to develop their phonological representations from relatively holistic forms into more structured levels, with the increment of spoken language experience and lexical entries during childhood. It is noteworthy that both the CI and NH groups showed ceiling-level or near-ceiling–level performance at the syllable detection task in this study. Although degraded acoustic signals are provided, children with CIs demonstrate comparable sensitivity to temporal and amplitude cues of speech as their NH peers (Nittrouer & Lowenstein, 2015). Despite device-inherent compromise in coding the precise temporal fine structure of the speech signal, children with CIs hold relatively robust sensitivity to holistic phonological structures as words and syllables, because these holistic forms are mainly distinguished by temporal and amplitude acoustic cues. In addition, prior studies suggested that syllable awareness is already well developed before 5 years of age in Mandarin-speaking children (Lin et al., 2020; Shu et al., 2008). There is also evidence that Chinese preschoolers with CIs can do fairly well in perception tasks of consonants, vowels, and lexical tones (Hong et al., 2019; H. Zhang et al., 2021; L. Zhang et al., 2018). Therefore, it is reasonable to observe nearly saturated performance on syllable-level awareness in all child participants in this study (with an age of around 6 years). Further research is needed to verify our findings with more challenging tasks as syllable deletion and syllable blending.

The lack of significant difference between the CI and NH groups in phonological detection of syllable-internal units (i.e., rime, onset, and tone) is noteworthy. The findings are partially in agreement with a prior study that revealed equivalent performances between Cantonese-speaking preschool-aged children with CIs and their peers with NH in rime and onset awareness, but not in tone awareness that CI children were outperformed by NH counterparts (Tse & So, 2012). Tse and So (2012) suggested that the compromised tone awareness in implanted children relative to NH controls could be attributable to the impoverished pitch information from CI devices that would contribute to the deficient lexical tone representations for children with CIs. Several plausible reasons are supposed for the inconsistent results in preschool-aged CI users' lexical tone awareness between the prior and present reports. One possibility could lie in different tonal repertoires between Cantonese and Mandarin. Cantonese has six lexical tones, whereas Mandarin involves four tones. Pitch distinctions of different tone types are more conspicuous for Mandarin than for Cantonese. For instance, the three level tones in Cantonese (i.e., Tone 1, Tone 3, and Tone 6) share flat pitch contour and can only be discerned by the subtle differences in pitch height. Moreover, Mandarin tones can be identified by the concurrent amplitude envelopes and duration patterns, apart from the primary pitch cues (Luo & Fu, 2004). However, Cantonese tones are cued almost exclusively on pitch contour and pitch height (Gandour, 1981). Taken together, Mandarin-speaking preschoolers with CIs could be more capable of achieving stunning tone awareness compared to the Cantonese-speaking counterparts who rely solely on the degraded pitch information provided by the CI devices. Additionally, another candidate possibility could be different hearing configurations for the child participants with hearing loss. In addition to the CI device, the vast majority of the clinical pediatrics (14 of 16) in this study were fitted with a contralateral HA in the contralaterally nonimplanted ear. A considerable amount of studies have documented that bimodal listeners (i.e., individuals with a combined use of CI and HA) would receive tangible benefits in tone perception, because acoustic low-frequency signals from the additional HA could complement the limited pitch signals from the CI device (H. Zhang, Zhang, Ding, & Zhang, 2020; H. Zhang, Zhang, Peng, et al., 2020; T. Zhang et al., 2010). A recent study revealed a positive effect of early bimodal stimulation on phonological skills in school-aged children with CIs (Nittrouer et al., 2016). Presumably, the improved pitch representations and phonological skills stemming from early bimodal experience might contribute to a better PA performance of lexical tones in the current preschoolers with CIs. However, a noteworthy caveat is that the overwhelming bulk of the recruited children with CIs were bimodal users, making it difficult to directly compare the outcome of bimodal stimulation with that of the CI-alone condition directly due to the existence of residual hearing in the bimodal users. As early bimodal hearing experience is beneficial for both PA and WM capacities in pediatric CI users (Nittrouer et al., 2017, 2016), a direct comparison between bimodal stimulation and a CI-alone condition is desirable with an employment of within-subject experimental design in future research.

Mixed results were observed regarding our running hypothesis of WM capacity. Preschoolers with CIs in this study showed optimal outcomes only for specific digit span tasks (i.e., ADS-B, CDS-F, and CDS-B). The deficit of ADSs for the CI population, especially in the forward digit span task, broadly replicated previous findings that pediatric CI recipients had difficulties in the storage component of verbal WM (e.g., AuBuchon et al., 2015; Nittrouer et al., 2013, 2017; Pisoni et al., 2011). These studies converged that CI users showed smaller digit spans or lower response accuracies relative to their NH controls in verbal WM tasks requiring a forward serial recall. The compromised verbal memory capacity for children with CIs is attributed to the degraded audibility of the CI device that hinders the phonological coding from storing immediate information in a short-term memory buffer (Nittrouer et al., 2017). These children may need to rely on a coarser kind of phonological structure to encode digits into the memory buffer because of the degraded signals they have access to. It is noteworthy that conventional digit span tasks with auditory presentation and oral response could confound the WM capacity with the comorbid deficits of audibility and speech production in pediatric CI users. Our study adopted CDS tasks, which mimicked the auditory tasks but eliminated the demands of audibility and production, to explore whether the fundamental memory mechanism underlies the deficit of WM capacity in preschoolers with CIs. The CI children reproduced comparable digit lists as NH controls in both forward and backward tasks of CDSs. It should be noted that the results were inconsistent with a recent report using the same design of the CDS tasks that revealed significantly poorer performance of CDS-F in CI users than NH controls (AuBuchon et al., 2015). The discrepant findings might result from different demographic characteristics of the CI participants between the two studies. AuBuchon et al. (2015) recruited a much older cohort of adolescent participants (around 14 years old) with relatively late cochlear implantation (implantation age before 7 years), whereas this study involved the preschool-aged children who were implanted at earlier ages (implantation age before 2 years). The auditory scaffolding hypothesis posits that a period of auditory deprivation in early life contributes to a delayed acquisition of sequential processing functions (Conway & Christiansen, 2005; Conway et al., 2009). Accordingly, the period of deprivation before cochlear implantation is the primary source of deficit. It follows that the amount of deficit in sequential processing abilities would be predicted by the length of auditory deprivation (Nittrouer et al., 2017). In other words, children who received their CI devices at earlier ages are more capable of developing typical functions of sequential processing that underlie the capacity of WM. Alternatively, there could be a critical period for developing the sequential processing abilities, and CI preschoolers in this study are all well within that period while receiving CIs (i.e., within the age of 2 years). This critical period exactly fits with the proposal that the development of verbal WM begins by 2 years of age (Cuevas & Bell, 2014). Therefore, it is reasonable to postulate that the pediatric CI users with an early implantation (i.e., within the age of 2 years) are equipped to develop typical sequential functions that lead to an equivalent capacity of WM as NH peers when verbal mediation is avoided. However, further research is needed to explore the underlying mechanism of WM and clarify the sequential processing functions in accounting for the development of WM capacity in young CI children and NH peers.

The positive correlation between performances of phonological detection and ADSs supports our hypothesis that poor awareness of phonological structure (i.e., deficient PA skill) is connected with diminished verbal WM capacity in preschoolers with CIs. The results are in line with the phonological bottleneck hypothesis, which was proposed to account for the diminished verbal WM in children with dyslexia. According to this account, the deficit of verbal WM in the pediatric dyslexic population predominately arises from poor PA (e.g., Bar-Shalom et al., 1993; Shankweiler et al., 1979). These children show deficits in serial recall of word lists, which is attributable to diminished sensitivity to phonological structure (Vellutino et al., 2004). In the same vein, a recent study by Romano et al. (2021) showed that phonological confusions represent the main error pattern of verbal WM in youth with CIs via error analysis of the serial recall performance of the letter–number sequencing (LNS) task. The results suggested that the fragile, underspecified phonological representations could contribute to deficits in verbal WM of CI children. These children may be restricted to relying on a coarser phonological structure for coding items into the memory buffers, a constraint that could result in delays in the development of their verbal WM capacity. In addition, a recent study by Nittrouer et al. (2017) demonstrated that the variability of verbal WM could be explained mainly by PA in children with NH, whereas the verbal WM variability in children with CIs could be explained primarily by vocabulary. In particular, vocabulary buildup reflects lexical restructuring that depends on the CI children's sensitivity to phonological structures. Following this account, the phonological bottleneck hypothesis could also serve as an explanation for the verbal WM variability found in their CI child participants. Our positive correlation findings provide corroborating evidence for expanding the phonological bottleneck hypothesis to explain verbal WM delays in these pediatric CI users. Moreover, a phonological loop component is involved in the dual-component model of WM by Baddeley (2003), which directly associates the verbal WM capacity with phonological coding of the auditory input. The significant linkage between PA skill and verbal WM capacity in preschool-aged children with CIs of this study fits with Baddeley's WM model that a phonological loop is used to extract the phonological structure of the speech input and then to encode word items into the memory buffer. From the perspective of clinical practices, intervention programs aimed at enhancing sensitivity to more refined phonological structures may improve PA skill in this clinical population, which could in turn facilitate improvements in their verbal WM and spoken language capacities. However, the rehabilitative prediction awaits validation through further empirical testing.

There are several limitations in this study. First, the current cross-sectional report only focused on examining the PA and WM in a cohort of preschool-aged children with CIs in comparison with their NH peers. Further investigations with a longitudinal design are needed to chart the developmental trajectory of PA and WM in

Mandarin-speaking children with and without NH. Second, only phonological detection and digit span tasks were adopted to investigate PA skill and WM capacity, respectively. A wide range of tests are feasible to assess the two fundamental core skills, such as syllable deletion and phoneme detection for PA (Tse & So, 2012) as well as nonword repetition and LNS for WM. In addition, the relatively small subject sample confined the foray into exploring the causal relationship between PA skill and WM capacity. In a nutshell, further longitudinal research with a large-scale subject pool gains a better understanding of PA and WM in Mandarin-speaking children with CIs and NH.

Conclusions

This study investigated PA skills and WM capacity in Mandarin-speaking preschool-aged children who received the CI devices at a relatively earlier age. With early implantation, these individuals were able to demonstrate age-appropriate abilities in phonological detections and specific digit spans. Moreover, the positive correlation between performances of phonological detection and digit span tasks further confirmed the inherent linkage between PA and verbal WM in the preschoolers with CIs. These results have practical implications for aural rehabilitation in this pediatric population.

Data Availability Statement

All data and R codes are available at https://osf.io/2qjpw/files/osfstorage.

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Appendix A

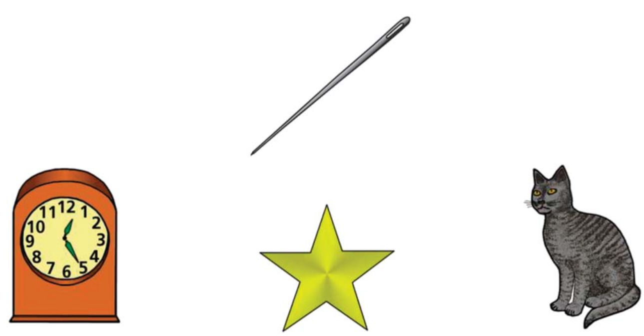
An Example of the Rime Detection Task

The upper picture indicates the target sound “tu4,” whereas the three lower pictures indicate three options: “ye4,” “fa4,” and “shu4,” respectively. The correct answer is “shu4,” which shares the rime “u” with the target.

Appendix B

An Example of the Onset Detection Task

The upper picture indicates the target sound “zhen1,” whereas the three lower pictures indicate three options: “zhong1,” “xing1,” and “mao1,” respectively. The correct answer is “zhong1,” which shares the onset “zh” with the target.



Appendix C

An Example of the Tone Detection Task

The upper picture indicates the target sound “yi3,” whereas the three lower pictures indicate three options: “ji1,” “bi3,” and “qi2,” respectively. The correct answer is “bi3,” which shares Tone 3 with the target.