Sonority-Related Novel-Word Learning Ability of Children with Cochlear Implants with Optimal Oral-Language Exposure

Yasmeen Hamza[1], Areti Okalidou[2], Ann Dierckx [3], Astrid van Wieringen[1],

[1] KU Leuven - University of Leuven, Department of Neurosciences, Research Group Experimental ORL

[2] University of Macedonia, Department of Educational and Social Policy

[3] University Hospital Leuven, Leuven, Belgium

Statement of Contribution: The first author designed, prepared, and conducted the experiment using the resources at KU Leuven, with contributions from the second and last author. The first and last authors have worked on the results, discussion and paper writing at all stages of the study. The second author was involved in the final stages of paper writing. The third author was involved for the recruitment of participants and implementation of the experiment at the University Hospital Leuven.

Disclosures/Conflicts of Interest and Source of Funding:

The research leading to these results has received funding from the People Programme (Marie Curie Actions) of the European Union's Seventh Framework Programme FP7/2007-2013/ under REA grant agreement n° FP7-607139 (iCARE).

Corresponding Author:

Address correspondence to Yasmeen Hamza, KU Leuven - University of Leuven, Department of Neurosciences, Research Group Experimental ORL, O&N II, Herestraat 49/721, Leuven, Belgium, 3000.

Email: yasmeenabdelkarimmohamed.hamza@kuleuven.be

ABSTRACT

Objectives The current study investigated how children with CIs, with optimal exposure to oral-language, perform on sonority-related novel-word learning tasks. By optimal oral-language exposure, we refer to bilateral cochlear implantation below the age of two years. Sonority is the relative perceptual prominence/loudness of speech sounds of the same length, stress, and pitch. The current study is guided by a previous study that investigated the sonority-related novel-word learning ability of a group of children with CIs, in the Greek language, of which the majority were implanted beyond the age of two unilaterally.

Design A case-control study with 15 Dutch-speaking participants in each of the three groups, i.e; children with CIs, normal-hearing children (NHC), and normal-hearing adults (NHA) was conducted using a sonority-related novel “CVC” word-learning task. All children with CIs are implanted before the age of 2 years with preimplant hearing aids. Thirteen out of the 15 children had bilateral cochlear implants. The CVC words were constructed according to four sonority conditions, where N is non-sonorous and S is a sonorous phoneme: NSN, NSS, SSN, and SSS. Outcome measures were accuracy and reaction times (RTs). In addition, the Peabody picture vocabulary test and the digit span forward test were administered to the children.

Results There were no statistical differences in accuracy or RTs between the children groups on the overall score, and across the different conditions. However, children with CIs, unlike NHC, scored statistically less accurately and with longer RTs relative to NHA, on the overall task. Within-group comparisons showed that none of the groups performed statistically differently on any of the conditions. The NHC showed higher receptive vocabulary scores relative to children with CIs. Additionally, the group of children with CIs entailed a statistically significantly higher number of children with “weak” short-term memory.

Conclusions Children with CIs who have optimal oral-language exposure showed age-appropriate sonority-related novel-word learning abilities and strategies relative to their NH peers. However, children with CIs continue to show lower receptive vocabulary scores than NHC, despite the equivalent novel-word learning ability. This suggests that children with CIs may have difficulties in retaining newly learned words. Future work should look into possible causes of the gap in performance. This would eventually aid in rehabilitation tailored to the needs of the individual.

INTRODUCTION

Children with Cochlear Implants

Cochlear implants (CIs) are considered to be standard care for children with bilateral profound sensorineural hearing loss (Wilson, 2015). As of 2010, the estimate of children with CIs worldwide is over 80,000 (Kral and O'Donoghue, 2010). The CI restores audibility, helps achieve speech perception, spoken word recognition, good spoken language levels, and allows for integration within oral society, both socially and academically for many CI users (van Wieringen and Wouters, 2015; Wilson, 2013; 2015). However, speech perception and communication performance outcomes remain highly variable (Kral and O'Donoghue, 2010; van Wieringen and Wouters, 2015). Multiple factors including the relatively degraded electrical transmission of the speech-related acoustic cues and auditory deprivation, in addition to other factors (neural degeneration, parental support and involvement, etiology of hearing loss, duration of CI use, type of CI, the modality of hearing, cognitive functions, and additional disabilities) are responsible for such variability (Jung et al., 2012; See et al., 2013; van Wieringen and Wouters, 2015). Contemporary CIs convey temporal envelope modulations in an excellent manner. The current greatest challenge for CI is the delivery of fine spectro-temporal cues (Lorenzi et al., 2006; Whitmal et al., 2015). The aim of the current study was to provide a better understanding of the effect of auditory deprivation on the perception and utilization of the speech-related acoustic cue of sonority, in addition to how those factors affect the novel word-learning (NWL) abilities of children with CIs. This would provide input for future rehabilitation aiming at reducing variability in outcomes.

Lexical Access, Novel-Word Learning, and Vocabulary Acquisition

Several interactive processes are involved when learning new words and building a lexicon. Figure 1 demonstrates a simplified summary of the processes involved. The process of learning a new word occurs over time as the child is exposed to the word in multiple varied contexts, which allows form-to-meaning linkage to be stored in lexical memory to develop receptive vocabulary (Gupta, 2005). Figure 1 starts with “fast mapping” which describes the first time the child creates the object-novel label association (Walker, 2013). After that, the child uses retention procedures to store the newly learned word in the long-term memory, to be part of a lexicon (Gupta, 2005). Later on, the child utilizes the existent lexicon to extend on it by creating new object-novel label associations (Hirsh-Pasek et al., 1999).

To learn new words, phonological representations need to be encoded and mapped onto meanings. Fast mapping is the ability to create the referent-novel word association after few exposures. Fast mapping includes both the ability to identify the correct referent (referent selection) and to retain this newly formed label–object mapping in the memory (Carey and Bartlett, 1978). The fast mapping retention ability is known to be fragile and greatly affected by the saliency of the referent and repetition (Walker and McGregor, 2013).

After the correct referent-novel word association has been made, the child needs to utilize retention processes to store the newly learned lexical representations in long-term memory as part of a lexicon, and to be able to use it later on (Markson and Bloom, 1997). Memory develops over time, skilled word learners use internal verbal rehearsal procedures to maintain words in working memory which facilitates the encoding of words into long-term memory and development of lexical representations (Gathercole and Baddeley, 1989).

To expand the lexicon, the child will utilize extension procedures. Extension is the knowledge that a word labels a group of similar objects, rather than only the original exemplar. Extension ability develops around the age of 2 years when the child develops the understanding that words can refer to categories. This involves determining the word's correct category extension, so they can extend to multiple exemplars of a referent (Hirsh-Pasek et al., 1999).

It is important to realize that the processes described are more interactive than sequential. For example, the child's existent lexicon (Storkel and Lee, 2011) and extension ability (Hirsh-Pasek et al., 1999) affects the success of fast mapping, the retention ability is affected by the saliency of the referent and repetition (Walker and McGregor, 2013), and the extension ability is affected by the existent lexicon (Hirsh-Pasek et al., 1999).

During the process of fast mapping, the child needs to first access the lexical unit. The process of lexical representation and access varies with development: early in life children adopt a holistic or less detailed lexical representations known as whole-word learning (Hallé and de Boysson-Bardies, 1994), later in life children develop more detailed representations using a smaller number of units (Bertoncini and Mehler, 1981; Vihman, 2016).

Template-driven word learning is whole-word processing, with a tendency for learning words with a particular prosodic frame. The word template acts as a lexical generalization pattern that later spurs further learning of words that fit into the same template. The template shape is dynamic rather than static, as the child's phonological knowledge increases and stabilizes. Once the child masters more variable and complex sequences of the adult language, template-driven word learning fades away from a child's phonological system (Macken, 1979; Vihman, 2016).

Fast-mapping studies focus on understanding what children learn about a word after minimal exposure to a new label (Jaswal and Markman, 2001). This ability develops during the period of whole-word learning (Jaswal and Markman, 2001). Novel-word test paradigms aim at replicating the complex process of fast mapping in a controlled environment. The tasks include exposing a child to a novel (and/or nonsense) word and a target referent followed by assessing the child's ability to associate the word with the referent (Carey and Bartlett, 1978; Davidson et al., 2014; Robertson et al., 2017; Spiegel and Halberda, 2011).

Sonority and Sonority-Related Language Phonotactics

Sievers (1881) linked sonority to audibility using a perceptual experiment, proposing that more audible sounds rank higher in sonority. Sonority (or vowel-likeness) is a scalar phonological/ phonetic aspect referring to the loudness or relative perceptual prominence of a particular segment compared to other sounds of the same length, stress, and pitch (Ladefoged, 1993; Parker, 2008). Speech sounds include vowels which are considered to be sonorous (S), while consonants could be sonorous (S) or obstruents (non-sonorous; NS) (Clements, 1990). Parker (2008) provided a novel physical correlate of sonority, in which sonority was viewed as the sound level extremes of phonemes: maxima for vowels and minima for consonants.

Sonority plays a grammatical role in defining within-syllable and across-syllable structure through language-universal phonotactic principles. According to the sonority sequencing principle (SSP), each well-formed syllable has a peak of sonority (usually a vowel) with the more sonorous consonants located closer to the peak and the less sonorous ones further away from it (Blevins, 1995). Sonority dispersion principle (SDP), derived from the SSP, states that the larger the degree of sonority rise from the onset to the nucleus of the syllable, and the smaller the fall from the nucleus to the coda is, the more optimal the sonority sequencing is (Clements, 1990). Therefore, the universal tendency for a sound to occur in a syllable coda vs. onset is directly proportional to how high vs. low it is in sonority, respectively (Blevins, 1995). In the application of the sonority-related sequencing principles as a language-universal rule, the ideal syllable ends in a vowel. However, if postvocalic consonants are present sonority should decline gradually (or remain level) from the nucleus of the syllable to the end of the coda. As the syllable structure becomes ill-formed (as defined by the SSP), listeners tend to systematically misidentify the syllable. This phenomenon has been documented in numerous languages e.g., English (Berent et al., 2011; Berent et al., 2009; Berent et al., 2007), French (Maïonchi-Pino et al., 2012), Hebrew (Berent et al., 2013), Korean (Berent et al., 2008), and continuous artificial speech (Ettlinger et al., 2012). Figure 2 demonstrates the impact of relative perceptual prominence and sonority-related grammatical rules on the CVC novel words. Vowels are always sonorous. By manipulating the consonants in each position, once to be sonorous and once non-sonorous, four possible sonority conditions were obtained: NSN, NSS, SSN, and SSS. As you move from the left end towards the right end of the continuum, the overall temporal envelope sound minima decreases with increasing perceptual prominence (SSS, followed by SSN and NSS, and finally NSN). All the sonority conditions respect SSP with a rise from the onset to the nucleus of the syllable and fall from the nucleus to the coda. In terms of SDP, the most optimal condition is NSS, as it has the maximum rise and the minimum fall, while the least optimal is SSN, as it has the least rise and the maximal fall, with a relative violation of the SDP where the fall is greater than the rise. In between lies the conditions NSN followed by SSS.

Profound Hearing Loss and Novel-Word Learning

Hearing impairment affects children's fast mapping (Davidson et al., 2014), word learning ability (Robertson et al., 2017; Stelmachowicz et al., 2004), vocabulary (Oktapoti et al., 2016), and the ability to learn phonological features of new words (Stelmachowicz et al., 2004).

Relatively few studies have assessed the NWL abilities of children with CIs (Davidson et al., 2014; Hamza et al., 2018; Houston et al., 2005; Houston and Miyamoto, 2010; Houston et al., 2012; Pimperton and Walker, 2018; Willstedt-Svensson et al., 2004). Prior to cochlear implantation, these children were exposed to a (preimplant) period of auditory deprivation. It is thus expected that children with CIs, following auditory deprivation, would have altered word-learning abilities that would affect their lexical acquisition. Houston et al. (2005) demonstrated that, on average, children with CIs perform poorer than NH peers on NWL tasks. However, with the universal neonatal screening programs, earlier detection of hearing loss and intervention with cochlear implantation has become feasible even within the first year of life (Roland et al., 2009). The importance of early oral-language exposure on the NWL abilities of children with CIs has been demonstrated through the correlations between young age of implantation and better NWL performance (Houston et al., 2005; Houston et al., 2012; Willstedt-Svensson et al., 2004). Furthermore, the ability of children with CIs to learn new words has been linked to good expressive/receptive vocabulary, phonological processing, and working memory span.

Study Motivation, Objectives, and Hypothesis

Sonority plays a role in NWL (lexical access and fast mapping) through the perceptual prominence cues and sonority-related grammatical rules. Given that temporal envelope cues are well conveyed and processed by CI users, children with CIs are expected to benefit from perceptual prominence cues. Davidson et al. (2014) have highlighted the role of audibility in NWL by demonstrating that children with CIs who possess greater audibility, as defined by a better pure tone average, had better NWL performance. In contrast, sonority-related grammatical rules are language-learning rules and therefore are expected to be delayed or hindered in children with CIs who are exposed to significant preimplant periods of auditory deprivation.

Hamza et al. (2018) examined the abilities of children with CIs to learn CV-CV novel words in different sonority conditions that rely on perceptual prominence cues vs sonority-related grammatical rules. The study included 15 children with CIs matched to 25 normal-hearing children (NHC) according to chronological age, and 50 normal-hearing adults (NHA). The mean age of implantation was 2;4 +/- 0;8, with more than two-thirds of participants implanted beyond their second year of age. All children had only one CI. Additionally, more than two-thirds did not receive hearing aids prior to implantation. Children with CIs showed higher accuracy performance on learning word templates with perceptually prominent components (SS-SS) relative to the words starting with a less perceptually prominent syllable (NS-SS, NS-NS). This pattern was not observed in NHC, who were equally accurate across all conditions. Therefore, even though both children groups did not differ in accuracy performance as an overall and across the different sonority conditions, they did perform differently in the different sonority conditions. High accuracy performance on the SS-SS word template NWL was further shown through the adult-equivalent performance of the group of children with CIs (4;11 – 15;2) on the perceptually prominent condition solely, whereas the group of NHC (3;9 – 15;2) showed adult-comparable performance on more than one condition. This led the authors to conclude that the children with CIs adopted the early-stage word learning strategy known as “template-driven word learning” using the static template of SS-SS. Additionally, children with CIs demonstrated significantly longer RTs relative to the NHC as an overall. The longer RTs by children with CIs were driven by the longer RTs on the SS-SS condition, relative to the NHC. The authors attributed the longer RTs on the SS-SS condition to high listening effort required by the children with CIs to reach such high-accuracy performance.

In an effort to understand the role of oral-language exposure on the sonority-related NWL (S-NWL) of children with CIs, Hamza et al. (2018) conducted a subgroup analysis. The subgroup analysis included 12 children with CIs matched to 12 NHC on the postimplant age (CIs: 3 ; 2 – 12 ; 8; NHC: 3 ; 8 – 13 ; 6). Results showed that children with CIs continued to show the same template-driven word learning pattern in terms of accuracy, as when matched on chronological age. However, both children subgroups showed no differences in RT performance. This led the authors to conclude that children with CIs exposed to preimplant periods of auditory deprivation continued to show the pattern of template-driven word leaning utilizing the static template of highly sonorous components (SS-SS), even after equivalent periods of oral-language (postimplant) exposure. Extended periods of postimplant oral-language exposure presumably reduced the listening effort. However, since the prolonged RT durations were initially driven by the SS-SS template, this could mean that children with CIs matched to NHC on postimplant age show enhanced template-driven word learning, since they no longer required extended RTs to achieve the high accuracy.

In the current study, we hypothesized that the children with CIs in the Hamza et al. (2018) study performed less accurately on conditions relying highly on sonority-related grammatical cues as a result of the significant preimplant periods of auditory deprivation, and quality of unilateral auditory input.

Early age of implantation is associated with better speech and language outcomes both receptively and expressively (Dettman et al., 2016; Driver and Jiang, 2017; Miyamoto et al., 2017; Nicholas and Geers, 2008; Niparko et al., 2010). Studies have shown that children who receive a CI below 18–24 months of age achieve better language outcomes than those implanted later (Dettman et al., 2016; Niparko et al., 2010). Furthermore, age-appropriate spoken language skills are more likely with younger age of implantation (Boons et al., 2012; Levine et al., 2016; Miyamoto et al., 2017), even after an average of 8.6 years of additional CI use (Geers and Nicholas, 2014). Studies have shown that children implanted below 2 years of age show significantly better auditory-verbal growth relative to children implanted younger than 3;6-4 years (Dettman et al., 2016). Additionally, children implanted younger than 2 years can show equivalent performance to their NH peers in some areas of language development (Levine et al., 2016). Moreover, Children with bilateral CIs have been shown to outperform unilateral users on both the receptive and expressive language outcomes (Boons et al., 2012; Sparreboom et al., 2015), as well as verbal intelligence (Jacobs et al., 2016). Therefore, we further hypothesized that the children with CIs, who are exposed to less significant auditory deprivation due to early bilateral implantation, would be able to perform well across the different sonority conditions, whether they rely on perceptual prominence or language-related grammatical cues, and that their manner of performance would be similar to that of their NH peers.

In Flanders (Dutch-speaking part of Belgium), newborn hearing screening, implemented since 1998, assesses around 96% of newborns (Desloovere et al., 2013). The screening program is integrated with the diagnosis of hearing loss, early intervention, and rehabilitation in a single program. Since the implementation of newborn hearing screening, the number of children with severe to profound hearing loss implanted prior to 18 months has drastically increased (De

Raeve, 2016). Furthermore, two CIs (simultaneous and sequential) are fully reimbursed by The Belgian National Health Insurance Institute for children less than 12 years of age since 2010 (van Wieringen and Wouters, 2015). Therefore, Flanders children with severe to profound hearing loss are likely to have been detected and implanted well before 2 years of age, with the younger ones detected after 2010 implanted bilaterally. Additionally, immediately after diagnosis, all children receive hearing aids to determine potential benefit from amplification, thereby ensuring early auditory exposure.

In the current study, we investigate whether profoundly hearing-impaired children who receive bilateral CIs before 2 years would be able to benefit from the different sonority cues as the NHC. This was investigated in a sample of Flemish children using a similar study design as in the Greek study (Hamza et al. 2018), with modifications to fit the Flemish language phonotactics.

MATERIALS and METHODS

Participants

A case-control study was conducted including three groups of Flemish-speaking participants: 15 children who received their CI(s) at the University Hospital Leuven were pair-matched with 15 NHC according to age, and 15 young NHA. The sample size of children with CIs was equal to the number of children with CIs in the Greek study (Hamza et al. 2018). The normal-hearing groups were matched in number. Children with CIs age ranged between 4;6 and 15;10, 6 were females and 9 were males. Children with CIs included in the present study were of relatively the same age range (within 4 months) as in Hamza et al. (2018). The minimum age was set to 4;6 guided by the finding of Nicholas and Geers (2008) that children who receive early CIs (12-16 months) are likely to overcome the language delays relative to NHC by the age of 4;6. Children with CIs had to be prelingually deaf and early implanted, as defined by an age of implantation of maximally 2 years. Participants had no additional disabilities and were within mainstream schools. All implanted devices were Cochlear^{TM} utilizing the ACE processing strategy. Recent mapping within the last 6 months and free-field pure-tone average (PTA) thresholds of equal or below 40 dB HL in the better hearing ear were also part of the inclusion criteria. Apart from two participants, all children were bilaterally implanted. Those two participants had no hearing aids on the contralateral ear, due to lack of residual hearing. The age at testing, age of implantation and postimplant age as defined by the earliest implant, aided laterality, preimplant and postimplant PTA thresholds of each of the children with CIs are depicted in Table 1. Normal-hearing children were pair-matched to the children with CIs within one chronological year (Mean=10;8, Range= 4;9-15;8, SD= 3;1). Inclusion criteria for the NHC included normal hearing, typical-development as evidenced by an average performance at school and age-appropriate receptive vocabulary and short-term memory scores.

Informed consents were obtained from all the participants older than 18 years. For participants younger than 18 years, consents were obtained from one of the parents. This study has been approved by the Medical Ethical Committee of the University Hospitals KU Leuven (approval number B322201523727).

Similar to the Greek study (Hamza et al., 2018), a battery of tests was selected including the S-NWL, audiological, and language tests, as described in the next section. Audiological tests included pure-tone audiometry to ensure normal hearing of the control groups. In addition, speech audiometry tests using the monosyllabic CVC ‘Vlaamse opnamen voor spraakaudiometrie’ NVA word lists (Wouters et al., 1994) were administered to document the speech recognition abilities of the children with CIs. The Peabody picture vocabulary test

(PPVT) (PPVT-III-NL; Schlichting, 2005), and the digit span forward test (DST) (CELF-4-NL; Kort, et al., 2008) were used to compare the receptive language scores and the short term memory of both children groups respectively, and to ensure that the NHC had at least average performance. The battery of tests took 40 minutes on average depending on the child's age and responsiveness. Aided free-field pure-tone average thresholds (500 Hz to 2 kHz), speech audiometry correct percent scores, PPVT (Schlichting, 2005) and DST (Kort et al., 2008) percentile of the children with CIs are depicted in Table 1.

Materials

Sonority Experiment

Sonority Related-Novel Word Learning Experiment Design and Stimuli

The S-NWL experiment was a computer-based, novel-word lexical identification task following the same design as the one used in the Greek Study (Hamza et al., 2018), with modifications of the word stimuli to follow the Flemish language phonotactics. This included the use of a different word template "CVC", as the "CV-CV" word forms are infrequent in the Flemish Language (Schiller et al., 1996). The CVC words were extracted from the lists of Bosman and Smoorenburg (1995), if not, they were derived by manipulating a phoneme in the word extracted (for example, there were no words with trills) in Bosman and Smoorenburg (1995) word lists. All CVC words were constructed using short vowels to avoid the confounding factor that in the Flemish Language, sonorant sounds are more prone to deletion in production following a long vowel (Fikkert, 1994). The short vowel /y/ and schwa vowel were excluded, as guided by Bosman and Smoorenburg (1995), since very few CVC words exist in Flemish with those vowels. Moreover, in the CVC final position, devoicing occurs to the obstruents (Schiller et al., 1996). Thus, only voiceless sounds in the final position were allowed.

In the current study, token effect was controlled for apriori by the creation of 4 different versions of the experiment with different token lists that were randomly assigned. Each experiment entailed 16 CVC words, within the four sonority conditions (SSS-SSN-NSS-NSN), illustrating novel objects (MacRoy-Higgins et al., 2013). Each version contains 9 words from the Bosman and Smoorenburg (1995) list and 7 derived words. The average frequency of occurrence of the CV and VC components of tokens of the 4 lists for each of the sonority conditions were within one standard deviation (SD) from the mean (CELEX 2; Baayen et al., 1995). We refer to Table 2 for an inventory of the S-NWL experiment stimuli, the sonority condition, and phonemic content.

Sonority-Related Novel Word Learning Experiment Procedure

Figure 3 illustrates the procedure for one trial, which was repeated for all the 16 trials of the experiment. Each trial consisted of a pair of CVC words of opposing sonority conditions guided by the Greek study (Hamza et al., 2018). The fast-mapping (Carey and Bartlett, 1978) procedure was used to familiarize the novel object with the specific novel word label. This was repeated for each novel word of the pair. Carrier phrases used for fast mapping were "This is a ___" and "Look, a ______." Then, an identification task with a choice of three picture array format including the two familiarized objects and a third foil object appeared with an audio playing "Show me + target word." The time lag between the slides was programmed to 1000 msec, to ensure that identification was based on the presentation of discrete trials. Both accuracy measures and RTs (from the offset of the target-word audio) were recorded and logged through the touch screen.

Sonority-Related Novel Word Learning Test Setting

Testing took place in a sound-treated booth of the ENT department of the University Hospitals Leuven. A story scenario[1] was developed to instruct the children. A practice session including six trials (two with real object words and four with novel words following the 4 sonority conditions) was employed before testing. The practice sessions followed the same procedures as the testing phase. A pass score criterion of above 50% in the trial session was mandatory before moving on to the testing phase. None of the participants in the current study required repetition of the practice session. One participant (other than the 15) could not pass the score criterion of the practice session, even after repetition, and therefore did not proceed to the testing phase. Hand position was standardized using a palm-shaped pad, with versions customized for left and right-handed participants. The stimuli were played through a single loudspeaker placed at 0° Azimuth calibrated at 70 dB HL at 70 cm from seating position. A single sound source was used to provide equal input to both sides. The testing session lasted 20 minutes including the practice.

Acoustical Analyses of the Sonority Experiment Audio-Stimuli

Novel word stimuli and carrier phrases were recorded by a native Flemish female speaker using Edirol R-4 Pro portable audio recorder in a sound-treated booth. Using Cool Edit Pro 2.1 (Cool Edit/Pro, version 2.1; Syntrillium Software, Phoenix, AZ, USA), the carrier phrase and the target

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[1] “Many strange things are in a Magic Box. They look funny and have funny names too. The computer will say their name a few times. Then the computer will ask you to choose one funny thing. It will say, "Show me-----". Once you hear the name, press with your finger at the screen, as quickly as possible (use gestures). Let's practice with some things that you know first!”

words were normalized separately to their averaged RMS of 32.535 dB HL. This was to ensure that the results under test were not due to differences in presentation intensity. The carrier phrases were then collated to the target words.

Acoustic analyses of the stimuli were conducted using the Parker (2008) methodology. The sound minima were used as a physical correlate of the sonority classes of nonsonorous and sonorous consonants per position (consult Supplemental Digital Content 1.doc for the detailed procedure of measurement). Figure 4 illustrates the token “xar” as an example of the measurements performed on PRAAT. Table 3 illustrates the intensity minima values recorded for the various phonemes in the CVC word stimuli. An independent-samples *t* test showed that the dB minimum value of the sonorous consonants were statistically higher than the nonsonorous consonants in the first position [t (62) = 8.514; p = 0.002] and the second position [t (62) = 8.063; $p < 0.001$]. Furthermore, four real Flemish words, that were recorded by the same speaker and used in the training phase, were analyzed using the same Parker methodology on PRAAT. **Table 4** shows that similar sonority intensity trends were observed for the sonorous vs nonsonorous sounds per position for the Flemish real words.

Visual Reaction Time Experiment

A nonverbal, visual task (Hamza et al., 2018) was administered, as a control condition, to ensure that the process of picture selection had no influence on the RT results. The absence of RT differences between groups on the visual task excludes generic motor differences in the process of picture selection between the compared groups. Eight trials presented a rabbit appearing on the screen in one of the three picture positions; the participant was instructed to catch the rabbit appearing on the screen as quickly as possible by touching the screen in the same manner as in the sonority experiment. The quickest visual RT of the eight trials was logged.

Data Analyses

The two major outcome performance measures of the sonority experiment were accuracy and reaction times. Accuracy was expressed in percent correct score, and RT was expressed in milliseconds. Performance accuracy was the primary outcome, and so only, the RTs of the accurate responses were analyzed. Furthermore, trials where the RT was not logged from the first touch of the screen due to technical failure, as reported by the tester present, were removed from the data set. The percent of trials eliminated from the RT data set was 5.83% for NHA, 6.67% for NHC, and 14.17% for children with CIs. An α level of 0.05 was used for all statistical tests.

The accuracy percentage scores in the S-NWL were not normally distributed even after $\log_{10}$ transformation. Therefore, nonparametric tests were applied to the raw untransformed data. For between-group comparisons, the Kruskal–Wallis test was used for main effects, followed by the Mann–Whitney *U* test. For within-group comparisons, the Friedman one-way analysis of variance (ANOVA) was applied, followed by the Wilcoxon test.

The visual task RT was normally distributed, as evidenced by the one-sample Kolmogorov-Smirnov test. The sonority experiment RT data were $\log_{10}$ transformed to achieve normality and homoscedasticity before being analyzed. For each of the visual and sonority RT data, one-way ANOVA's were used for between-group comparisons with independent variable "Group" and dependent variable "RT" with post hoc tests using the Bonferroni correction for multiple comparisons. Repeated-measures one-way ANOVA was used for within-group comparisons, with post hoc tests using the Bonferroni correction for multiple comparisons. For conceptual reasons, RT data are reported as untransformed raw values.

Pairwise and post hoc comparisons were done even in the absence of main effects to ensure that there were no differences between the groups.

For normally distributed data, a Bayes factor (BF) was calculated using Bayes factor independent sample test for pairwise comparison, and a Bayes factor related sample test for within-group comparison. The Bayes factor (BF) estimates the strength of evidence towards the null or alternate hypotheses. A BF of 1 indicates equal support for the null and alternate hypotheses. A BF smaller than 1 shows increasing levels of support of the alternate hypothesis over the null hypothesis, whereas a BF greater than 1 indicates evidence in favor of the null hypothesis over the alternate hypothesis (Jarosz & Wiley, 2014). The interpretations of Bayes factor values in the current study are based on Jeffreys' (1961) recommendations.

Data were analyzed using IBM SPSS software package version 20.0 (Kirkpatrick and Feeney, 2013).

RESULTS

Demographics

The mean chronological age of the children with CIs in the Greek and Flemish studies was not statistically different [t (28) = 1.489; $p = 0.148$]. However, the children with CIs in the two studies differed statistically in terms of the age of implantation [t (28) = 6.105; $p < 0.001$] and consequently the postimplant age [t (28) = 2.699; $p < 0.012$]. Therefore, we can conclude that the children with CIs in the current study show no difference in chronological age to those of Hamza et al. (2018), but are exposed to an earlier and longer duration of oral-language exposure. Furthermore, the Flemish study entailed a statistically significantly higher number of children with bilateral CIs (Chisquare test of independence, $\chi2 = 19.548$; df = 1; $p < 0.001$). Table 5 shows the chronological age, implantation age, postimplant age, and the number of children with two CIs in each of the two studies.

Performance on S-NWL Task by the Different Groups

Accuracy Performance

The accuracy performance on the S-NWL ranged between 87.5% and 100% for the NHA group, 81.25% and 100% for the NHC group, and 75% and 100% for children with CIs. Median accuracy performance was 100% for the NHA group, whereas it was 93.75% for each of the children groups, as illustrated in Figure 5.

Kruskal–Wallis analysis showed no statistically significant main effect of group on the overall accuracy performance (p=0.129), as well as on each of the sonority conditions (NSN: p = 0.145; NSS: p = 0.784; SSN: p = 0.195; SSS: p = 0.731). However, further pairwise comparison using Mann–Whitney *U* test showed that the NHA performed statistically significantly more accurately than children with CIs on the overall task (U = 67; df = 29; p = 0.046).

Within-group comparisons using Friedman one-way ANOVAs showed that there was no main effect of the sonority condition on accuracy performance for all groups [NHA: $\chi2(3) = 1.435$; p = 0.697, NHC: $\chi2(3) = 0.714$, p = 0.870, CIs: $\chi2(3) = 1.849$, p = 0.604]. Further pairwise comparison using the Wilcoxon test confirmed that none of the groups performed significantly different on any of the conditions ($p>0.05$). Group performance within and across the different sonority conditions is shown in Figure 6.

Accuracy performance on the S-NWL task by NHC was positively correlated with age ($r=0.740$, $p= 0.002$). Accuracy performance on the S-NWL task by the children with CIs did not correlate with age ($r=0.140$, $p=0.618$), age at implantation ($r=-0.130$, $p=0.645$), nor postimplant age ($r= 0.164$, $p=0.559$).

Reaction Time Performance

Analysis of the RTs on the visual task experiment using one-way ANOVA showed that there is no statistically significant main effect of the test groups on the RT [$F(2,42) = 3.044$; $p = 0.058$]. Post hoc tests with Bonferroni correction for multiple comparisons further showed that there were no statistically significant RT differences between any of the groups on the visual task ($p>0.05$). Bayes analyses showed anecdotal evidence in favor of the alternate hypothesis on comparison between adult and both children groups (BF-NHC = 0.499; BF-CI = 0.432). Comparison between the two children groups revealed moderate evidence in favor of the null hypothesis (BF = 3.809). Collectively, statistical analyses support the absence of RT difference on the visual task between the groups of children. However, differences between the adult and children groups cannot be fully explained. Group performances on the visual task are depicted in Figure 7.

With regard to the average RT on the S-NWL, one-way ANOVA indicated a statistically significant main effect of group on the average RT [$F(2,42) = 8.779$; $p=0.001$, $\eta2 = 0.295$]. Post hoc analysis with Bonferroni correction for multiple comparisons showed that the NHA (mean = 287 msec; SD = 88 msec) yielded statistically significantly faster RTs than children with CIs (mean = 824 msec; SD = 435 msec; $p < 0.001$), but not NHC (mean = 571 msec; SD = 417 msec; $p = 0.097$). The children groups did not show statistically different RTs on the sonority treated lexical perception task ($p = 0.165$). Bayes analyses showed moderate and strong evidence in favor of the alternate hypothesis on comparison of the adult group to NHC (BF = 0.279), and children with CIs (BF = 0.003) respectively. Comparison across children groups showed anecdotal evidence in favor of the null hypothesis (BF = 1.276). Collectively, statistical analyses support the absence of RT difference on the S-NWL task between the children groups, and the presence of RT difference on the S-NWL task between the NHA and children with CIs. However, given the contrast between the interpretation of the p value and the BF, differences between the NHA and NHC groups cannot be fully validated.

Similarly, across group comparisons, using one-way ANOVAs, for each sonority condition, showed a main effect of the different experimental groups on the reaction time for all sonority conditions [NSN: $F(2,42) = 6.833$; $p = 0.003$, $\eta 2 = 0.246$; NSS: $F(2,42) = 9.062$; $p = 0.001$, $\eta 2 = 0.309$; SSN: $F(2,42) = 7.505$; $p = 0.002$, $\eta 2 = 0.263$; SSS: $F(2,42) = 6.040$; $p = 0.005$, $\eta 2 = 0.223$]. Post hoc analysis with Bonferroni correction for multiple comparisons showed that the NHAs were statistically significantly faster on all conditions than children with CIs ($p<0.005$), but not NHC (NSN: $p = 0.196$, NSS: $p = 0.061$, SSN: $p = 0.161$, SSS: p = 0.176). Bayes analysis showed anecdotal- strong evidence in favor of the alternate hypothesis on comparison of the adult group to NHC (NSN: 0.327, NSS: 0.087, SSN: 0.475, SSS: 0.644), and strong- extreme evidence in favor of the alternate hypothesis in comparison to children with CIs (NSN: 0.028, NSS: 0.007, SSN: 0.006, SSS: 0.008). Comparison between the children groups showed that the RTs of the two groups were not statistically significantly different on all sonority conditions (NSN: $p = 0.235$, NSS: $p = 0.221$, SSN: $p = 0.198$, SSS: p = 0.406). Bayes analysis showed anecdotal evidence in favor of the null hypothesis for the children groups (NSN: 1.48, NSS: 1.458, SSN: 1.391, SSS: 1.968). The RTs on the different sonority conditions, across the experimental groups, are shown in Figure 8.

Within-group comparisons using 3 repeated-measures one-way ANOVAs showed that for all groups there was no main effect of sonority conditions on the RT [NHA: $F(3, 42) = 2.071$, $p = 0.118$, $\eta 2 = 0.129$; NHC: $F(3, 42) = 0.083$, $p = 0.969$, $\eta 2 = 0.006$; CI: $F(3, 42) = 0.489$, $p = 0.692$, $\eta 2 = 0.034$]. Post hoc analysis with Bonferroni correction for multiple comparisons further validated that there was no difference in RT across sonority conditions for each of the 3 test groups ($p>0.05$). Bayes analyses showed anecdotal-moderate evidence in favor of the null hypothesis on comparison of RT across the different sonority conditions, for each of the 3 groups (BF = 1.133- 5.144).

Performance on Language-Related Parameters by the Children Groups

All NHC were TD as validated through the normal-hearing thresholds at all frequencies, reported average school performance, and average PPVT (Schlichting, 2005) and DST (Kort et al., 2008) scores.

Performance on PPVT (Schlichting, 2005)

An independent-samples *t* test comparison of the PPVT (Schlichting, 2005) percentile scores of the 2 children groups showed that NHC scored statistically significantly higher than the children with CIs [$t\ (28) = 4.179$; $p < 0.001$], as shown in Figure 9. Bayes Factor (0.009) showed extreme evidence in favor of the alternate hypothesis. Chi-square test of independence showed that the group of children with CIs entailed a statistically significantly higher number of children with "weak" receptive vocabulary relative to the NHC (NHC=0%, CI=53.3%; Chi-square test of independence, $\chi 2 = 14.067$; df = 1; $p = 0.002$). Accuracy performance on the S-NWL task were correlated positively with PPVT raw scores (Schlichting, 2005) (r=0.697, p=0.004) for NHC, but not children with CIs (r= -0.209, p=0.454). Reaction times were not correlated with PPVT raw scores for both NHC (r= -0.384, p=0.175), and children with CIs (r= -0.015, p=0.959) after correction for age. Correction for age was rationalized by the generic effect of age on RTs.

Performance on DST (Kort et al., 2008)

An independent-samples *t* test comparison of the DST percentile scores (Kort et al., 2008) of the 2 children groups showed no statistically significant difference [*t* (24.014) = 1.167; *p* =0.255], as shown in Figure 9. Bayes analysis showed anecdotal evidence (BF=2.151) in favor of the null hypothesis for the children groups. However, chi-square test of independence showed that the group of children with CIs entailed a statistically significantly higher number of children with "weak" short-term memory relative to the NHC (NHC=0%, CI=46.67%; Chi-square test of independence, $\chi 2 = 11.869$; df = 1; $p = 0.006$).

The Relationship between Fast mapping, Retention and Receptive Vocabulary

Accuracy and RT (after correction for age) performance on the S-NWL task were not correlated with DST raw score for both NHC (Accuracy: r= 0.199 p=0.476; RT: r= -0.301, p=0.295) and the children with CIs (Accuracy: r= -0.297, p=0.283; RT: r= 0.03, p=0.920). The lack of correlation between S-NWL measures and DST scores could mean that the current S-NWL task is not a good predictor of the retention processes necessary for building a lexicon. In Contrast, DST raw scores were correlated with PPVT raw scores for both NHC (r=0.562, p=0.029) and children with CIs (r= 0.694, p=0.004) suggesting the role of working/short-term memory in developing a lexicon. Figure 10 depicts the correlations between S-NWL scores and PPVT scores, as well as between DST raw scores and PPVT raw scores among the two children groups.

DISCUSSION

The current study investigated how well children with CIs, with optimal exposure to oral-language, perform on S-NWL tasks. By optimal oral-language exposure, we refer to reduced auditory deprivation through cochlear implantation below the age of two years and bilateral hearing. Hamza et al. (2018) previously demonstrated that children with CIs may be adopting template-driven word learning with the preferred template of words entailing perceptually prominent components (SS-SS), even after equivalent postimplant auditory exposure period to NHC. In Hamza et al (2018), the majority of children with CIs was implanted beyond the age of two with no hearing aids prior to implantation. Furthermore, all the children listened with one CI. This led to the current hypothesis that the template-driven word learning performance of the children with CIs in the Greek study could be attributed to preimplant periods of auditory deprivation.

To test the hypothesis concerning the benefit of optimal oral-language exposure, we employed test-paradigms similar to the Greek study but adapting to language-specific phonotactics. For example, the word structures used in the Greek and Flemish studies were slightly different: “CV-CV” vs. “CVC” respectively. However, those were the simplest label word forms possible in both languages in terms of medium frequency of occurrence. In the Greek study’s subgroup analysis, children with CIs showed an accuracy score of 83%-100%, while in the current study children with CIs accuracy scores ranged between 81 and 100%. Both studies showed high accuracy scores (ceiling effect), yet in the Greek study, a sonority effect was shown for children with CIs in the form of template-driven word learning, unlike in the Flemish study. The aim of the current study was to identify if children with CIs who are implanted bilaterally at an earlier age would not show reliance on sonority saliency cues and develop more age-appropriate word-learning strategies, where they can learn words of different sonority templates with equal accuracy. The difference between the children with CIs in the Greek and Flemish study was statistically significant with regard to implantation below the age of two and bilateral CIs.

The current study has provided additional evidence of the role of optimal oral-language exposure on the auditory processing skills of children with CIs. Hamza et al. (2018) demonstrated that longer RTs were required by children with CIs when matched to NHC on chronological age, but not when matched on postimplant age. This highlighted the importance of oral-language exposure in the form of postimplant exposure on RTs. In the Flemish study, children with CIs did not differ in RTs from age-matched NHC. This finding, in turn, denotes the importance of oral-language exposure in the form of early bilateral implantation on auditory processing and possibly listening effort experienced by the children with CIs, as expressed through RTs. Despite the fact that both children groups showed no difference in RTs, NHC showed adult-comparable RTs, while children with CIs lagged behind NHA RTs. However, the NHA-equivalent RT achieved by NHC is not supported by BF, and therefore it is possible that with a larger sample size that the NHC would also lag behind NHA. Furthermore, differences in RT between NHA and children groups could be due to generic motor differences, as shown by Visual RT BF.

Novel-word learning Ability

Our data corroborate previous reports on the role of early implantation and bilateral hearing on the language outcomes of children with CIs (Boons et al., 2012; Nicholas and Geers, 2008;

Niparko et al., 2010). Both child groups performed similarly overall and scored with similar accuracies and reaction times in each sonority condition. Most importantly, they were capable of learning words that follow the language phonotactics, regardless of whether they rely on perceptual prominence cues or sonority-related grammatical rules. Unlike Hamza et al. (2018), children with CIs in the current study did not adopt different/ delayed word learning strategies as the static template-driven word learning exhibited by the children with CIs in the Greek study.

In the current study sample, children with CIs were as skilled as NHC at “fast mapping” novel sonority-related phonological information under simple testing conditions. This shows that children within the current study may have more developed phonological knowledge. It is documented that for TD children, once more complex sequences of the adult language are mastered, template-driven word learning fades from a child’s phonological system (Macken, 1979). Although 2 years of age (Greek study) is already considered very good for exposure to language, the current study shows that children implanted below this age, who present no other disabilities, and who have optimal exposure through bilateral hearing, perform even more in line with NH listeners. Similarly, Quittner et al. (2016) have demonstrated that children who were implanted before the age of 2 outperformed those implanted beyond the age of 2 on a NWL task.

The impact of early rich/frequent oral-language exposure on word learning has been demonstrated for individuals with hearing impairment (Robertson et al., 2017; Stelmachowicz et al., 2004). Earlier studies have demonstrated that children with CIs perform poorer than NHC on word learning tasks (Houston et al., 2005). However, since then, the age of implantation has significantly dropped, as a result of the advancement in screening, diagnosis, and technologies (Roland et al., 2009). More recently, Pimperton and Walker (2018) showed that the word learning abilities of a group of children implanted during their first three years of life, with a postimplant age of at least 4 years, was similar to their NH age-matched peers. Davidson et al. (2014) have demonstrated that the NWL ability of children with CIs who received their first implant at 24 months on average falls below NH levels. However, the role of age of implantation on the NWL ability was demonstrated through positive correlations between younger age at implantation and better NWL and vocabulary scores. This has been demonstrated in several other studies, as well (Houston et al., 2005; Houston et al., 2012; Willstedt-Svensson et al., 2004). In the current study, the age of implantation did not correlate with the S-NWL abilities in terms of accuracy and RTs. However, the age of implantation in the current study was restricted by the inclusion criteria to a range of 0;4 and 1;11 resulting in limited variability especially with the small sample size and ease of the task.

Looking at the performance of the 2 children that had unilateral implants, aged 10;9 and 13;7, they were able to perform the task with high accuracy (100%). However, looking at their RTs, it appears that unilateral CI children might still employ early word-learning strategies. One of the two CI subjects showed longer RT for NSS condition, which relies highly on SDP, while the other showed shorter RTs for the sonorous conditions (SSS). Consult Supplemental Digital Content 2.doc for a table comparing the performance of each of the unilateral CI subjects to the average performance of the 13 bilateral implantees.

Receptive Vocabulary

Despite the NHC-equivalent performance of children with CIs on the S-NWL task, children with CIs in the current study showed poorer receptive vocabulary relative to NHC. Refer to Figure 1, while children with CIs in the current study may possess NWL abilities that are relatively well-developed as NHC, yet additional factors are responsible for them not reaching NHC-equivalent receptive vocabulary. Since S-NWL and PPVT tests are measuring different abilities, it appears that for children with CIs, the fast mapping ability and the receptive vocabulary acquired are not necessarily hand in hand. This is further expressed by the lack of a statistically significant correlation between the S-NWL and receptive vocabulary scores for children with CIs but not for NHC.

In contrast, previous studies have shown a relationship between vocabulary size and the ability to process new words –nonsense words- for NHC (Edwards et al., 2004), and children with CIs (Pimperton and Walker, 2018; Walker and McGregor, 2013). The lack of correlation between S-NWL performance and vocabulary could be due to the small score range and small sample size. However, NHC showed a correlation despite being of equivalent sample size and showing a similar score range. Other possible differences between the current and previous studies include the wide age range of the children with CIs in the current study with much older participants, and the nature of the word stimuli used in the word learning experiment. Pimperton and Walker (2018) utilized real word stimuli of low frequency of occurrence, while Walker and McGregor (2013) used novel words for which frequency of occurrence was not mentioned to be selective. The stimuli used in the current experiment were composed of CV and VC components of medium frequency of occurrence, unlike in vocabulary assessments where children were exposed to words of various frequencies of occurrence, as well as words that are more complex and of longer duration. Frequency of occurrence plays a role in the recognition and lexical access of words with the more frequent components more accurately and faster recognized (Storkel and Lee, 2011).

Thus, the simple S-NWL task is not necessarily the best predictor of the lexical learning abilities of children with CIs, as it is not representative of the challenging real-life situations in which they have to acquire new vocabulary. Children in the current experiment were required to learn a limited number (16) of simple monosyllabic words, one at a time within a very structured fast-mapping procedure. This is an atypical situation to what they are exposed to in real-life when acquiring new words. Therefore, future studies need to implement NWL paradigms that replicate real-life scenarios and use more complex word structures and of varying frequency of occurrence.

The current study does not imply that children with early CIs do not rely on sonority-related cues or that NWL ability is not an important predictor of language development. It is possible that children with CIs in the current study would rely on sonority-related cues in more difficult conditions, such as in conditions that employ more complex word forms, a greater number of tokens, and difficult listening conditions. However, what this study implies is that children with CIs with optimal oral-language exposure do not adopt deviant sonority-related early word learning strategies in simple testing conditions.

Retention Ability

The gap between the S-NWL ability and the receptive vocabulary scores of children with CIs, when compared to NHC, could also mean that children with CIs have well-developed fast mapping abilities, but not the ability to retain those lexical representations in their memory to be part of a lexicon, as expressed by their poor PPVT scores. Referring to Figure 1, children should be able to retain the newly learned lexical representations in long-term memory (Markson and Bloom, 1997). While the fast-mapping stage of word learning is a first and crucial step for lexical development, yet there is more (Houston et al., 2005). Fast-mapped representations are rarely strong enough to support naming performances, as opposed to strong above-chance-level performance on a forced-choice recognition test (Walker and McGregor, 2013) as the current S-NWL task.

Phonological working memory has been strongly associated with vocabulary size in NHC (Gathercole and Baddeley, 1989). Studies have shown that children with CIs have an atypical working /short-term memory capacity, which could be the result of an impaired ability to use verbal rehearsal procedures to maintain phonological information in working memory (Dillon et al., 2004; Pisoni and Cleary, 2003; Talli et al., 2018). In the current study, children with CIs entailed a larger number of children who scored weak on the DST (Kort et al., 2008). Furthermore, higher receptive vocabulary scores correlated with higher DST (Kort et al., 2008) scores for both children groups indicating the role of working/short-term memory capacity on developing a lexicon. Kronenberger et al. (2013) showed that the development of working and short term memory over a period of at least 2 years in children with CIs aged 6 to 16 years was related to the vocabulary and language comprehension growth rate.

Whether the proposed impaired/delayed ability to retain words is a result of poor working memory components e.g. the facilitator verbal rehearsal and binding procedure (Baddeley, 1986; 2000), or impairments in long-term memory storage and retrieval is questionable. Such proposed impairments in memory can be validated by testing children with CIs who have optimal-oral language exposure in immediate and delayed conditions using more complex stimuli and test paradigms. Immediate conditions, as in the current study, assess short-term/ working memory, and delayed conditions administered after at least 30 minutes up to weeks afterwards assess long-term memory (Baddeley, 1990). Houston et al. (2005) demonstrated that children with CIs performed similarly in both immediate and delayed conditions. However, children with CIs in the mentioned study already had poorer word learning abilities than NHC. Additionally, when the analysis included unfamiliar words only, children with CIs performed worse on the delayed condition, which suggests impairments in the long-term memory. More recently, Walker and McGregor (2013) demonstrated that a group of children with CIs implanted below the age of 3 years and were as young as 3;6, performed marginally worse on fast mapping, and worse on retention, which is in line with the current study findings.

Finally, it is important to note that the acquisition of words is impacted by several variables in addition to memory capacity. Factors as the frequency of exposure, repetition, attention, and extension are important for building up vocabulary (Hart and Risley, 1995; Hollich et al., 2000; Huttenlocher et al., 1991; Schwartz, 2015).

Conclusions

We can conclude that children with CIs who have optimal oral-language exposure in the form of early implantation before the age of two and bilateral hearing did not demonstrate the sonority-related early-word learning strategies demonstrated by Hamza et al. (2018). While fast mapping is an important first step in building a lexicon, however, it takes much more to develop language. Children with CIs in the current study showed lower receptive vocabulary scores than NHC, despite the equivalent NWL ability.

Limitations and Future Research

Future work should probe possible causes of the gap in performance between the NWL ability and the receptive vocabulary built. This includes testing immediate and delayed recall conditions, running longitudinal studies to see whether children with CIs would eventually catch up, using more complex paradigms and difficult listening conditions.

It is important to realize that the S-NWL task in the current experiment is rather structured and does not reflect real-life situations. Therefore, the NH-equivalent performance on the S-NWL task could be the result of the simple stimuli and experiment structure. The simple structure used was an essential first step to allow us to draw conclusions and further build on. Further research needs to construct NWL experiments that reflect incidental learning more closely, as in storytelling. The validity of the NWL paradigm used in the current experiment needs to be assessed by comparing it with more real-life scenarios. Additionally, children with CIs in the current study were tested in optimal conditions including sound-treated rooms, controlled stimuli output through speakers, and directed attention. More studies need to look into the effect of challenging listening conditions, including noise, on the NWL abilities of children with CIs.

Given the limited sample size, it is possible that a larger degree of evidence could be shown with larger sample sizes. This is particularly true for accuracy scores where BF was not calculated, and for the differences in RT between NHA and NHC where the BF supported the alternate hypothesis while the p value was >0.05. Future studies comparing the performance of children with CIs with optimal language exposure vs less optimal language exposure within the same study, if applicable, could be more conclusive.

ACKNOWLEDGEMENTS

Our special thanks go to all participants. We are grateful to our master’s students, Ione Van Bets, and Lola Vanderweyen for their help with data collection. We would also like to thank Prof. Wivine Decoster for her recordings, and Prof. Hans Smessaert for his knowledge on the Flemish Language linguistics and phonotactics.

Thanks to Michelle MacRoy-Higgins for providing permission to use the pictures of the novel objects. The research leading to these results has received funding from the People Programme (Marie Curie Actions) of the European Union's Seventh Framework Programme FP7/2007–2013/under REA grant agreement no. FP7-607139 (iCARE).

REFERENCES

Baayen, R H., Piepenbrock, R., Guliker, L (1995). *CELEX2 LDC96L14*.

Baddeley, A. D. (1986). *Working memory Oxford*. England: Oxford Uni.

Baddeley, A. D. (1990). *Human memory*. Boston: Allyn and Bacon.

Baddeley, A. D. (2000). The episodic buffer: a new component of working memory? *Trends in cognitive sciences, 4*(11), 417-423.

Berent, I., Harder, K., Lennertz, T. (2011). Phonological universals in early childhood: Evidence from sonority restrictions. *Lang Acquis, 18*(4), 281-293.

Berent, I., Lennertz, T., Jun, J., Moreno, M. A., Smolensky, P. (2008). Language universals in human brains. *Proc Natl Acad Sci USA, 105*(14), 5321-5325.

Berent, I., Lennertz, T., Smolensky, P., Vaknin, V. (2009). Listeners' knowledge of phonological universals: Evidence from nasal clusters. *Phonology, 26*(1), 75-108.

Berent, I., Steriade, D., Lennertz, T., Vaknin, V. . (2007). What we know about what we have never heard: Evidence from perceptual illusions. *Cognition, 104*(3), 591-630.

Berent, I., Vaknin-Nusbaum, V., Balaban, E., Galaburda, A. M. (2013). Phonological generalizations in dyslexia:The phonological grammar may not be impaired. *Cogn Neuropsychol, 30*(5), 285-310.

Bertoncini, J., Mehler, J. (1981). [Perception in newborn infants]. *Rev Prat, 31*(5), 387-388, 391-382, 395-386.

Blevins, J. (1995). The syllable in phonological theory. In J. A. Goldsmith (Ed.), *The handbook of phonological theory. Blackwell handbooks in linguistics* (pp. 206-244). Cambridge, MA, Oxford: Blackwell Publishers.

Boons, T., Brokx, J. PL., Frijns, J. HM., Peeraer, L., Philips, B., Vermeulen, A., et al. (2012). Effect of pediatric bilateral cochlear implantation on language development. *Archives of pediatrics & adolescent medicine, 166*(1), 28-34.

Bosman, A. J., Smoorenburg, G. F. (1995). Intelligibility of Dutch CVC Syllables and Sentences for Listeners with Normal Hearing and with Three Types of Hearing Impairment. *Audiology, 34*(5), 260-284.

Carey, S., Bartlett, E. (1978). Acquiring a single new word *Papers and reports on child language development* (Vol. 15). Stanford, CA: Stanford University, Department of Linguistics.

Clements, G. N. (1990). The role of the sonority cycle in core syllabification. In J. Kingston & M. E. Beckman (Eds.), *Papers in Laboratory Phonology I: Between the grammar and the physics of speech.* (pp. 283-333). Cambridge: Cambridge University Press.

Davidson, L. S., Geers, A. E., Nicholas, J. G. (2014). The Effects of Audibility and Novel Word Learning Ability on Vocabulary Level in Children with Cochlear Implants. *Cochlear implants international, 15*(4), 211-221. doi: 10.1179/1754762813Y.0000000051

De Raeve, L. (2016). Cochlear implants in Belgium: Prevalence in paediatric and adult cochlear implantation. *Eur Ann Otorhinolaryngol Head Neck Dis, 133 Suppl 1*, S57-60. doi: 10.1016/j.anorl.2016.04.018

Desloovere, C., Verhaert, N., Van Kerschaver, E., Debruyne, F. (2013). Fifteen years of early hearing screening in Flanders: impact on language and education. *B-ENT, 21*, 81-90.

Dettman, S. J., Dowell, R. C., Choo, D., Arnott, W., Abrahams, Y., Davis, A., et al. (2016). Long-term Communication Outcomes for Children Receiving Cochlear Implants Younger Than 12 Months: A Multicenter Study. *Otology & Neurotology*, *37*(2), e82-e95. doi: 10.1097/mao.0000000000000915

Dillon, C. M., Cleary, M., Pisoni, D. B., Carter, A. K. (2004). Imitation of nonwords by hearing-impaired children with cochlear implants: segmental analyses. *Clinical Linguistics & Phonetics*, *18*(1), 39-55.

Driver, S., Jiang, D. (2017). Paediatric cochlear implantation factors that affect outcomes. *European Journal of Paediatric Neurology*, *21*(1), 104-108. doi: https://doi.org/10.1016/j.ejpn.2016.07.012

Edwards, J., Beckman, M. E., Munson, B. (2004). The interaction between vocabulary size and phonotactic probability effects on children's production accuracy and fluency in nonword repetition. *Journal of speech, language, and hearing research, 47*(2), 421-436.

Ettlinger, M., Finn, A. S., Kam, C. L. Hudson. (2012). The effect of sonority on word segmentation: Evidence for the use of a phonological universal. *Cogn Sci*, *36*(4), 655-673.

Fikkert, P. (1994). On the acquisition of rhyme structure in Dutch. *Linguistics in the Netherlands 11*, 37–48.

Gathercole, S. E., Baddeley, A. D. (1989). Evaluation of the role of phonological STM in the development of vocabulary in children: A longitudinal study. *Journal of memory and language*, *28*(2), 200-213.

Geers, A., Nicholas, J. (2014). Enduring advantages of early cochlear implantation for spoken language development. *J Speech Lang Hear Res*.

Gupta, P. (2005). Clinical Issues: What’s in a Word? A Functional Analysis of Word Learning. *Perspectives on language learning and education*, *12*(3), 4-8.

Hallé, P. A., de Boysson-Bardies, B. (1994). Emergence of an early receptive lexicon: infants’ recognition of words. *Infant Behavior and Development*, *17*, 119-129.

Hamza, Y., Okalidou, A., Kyriafinis, G., van Wieringen, A. (2018). Sonority's Effect as a Surface Cue on Lexical Speech Perception of Children With Cochlear Implants. *Ear Hear, 39*(5), 992-1007. doi: 10.1097/aud.0000000000000559

Hart, Betty, Risley, Todd R. (1995). *Meaningful differences in the everyday experience of young American children*: Paul H Brookes Publishing.

Hirsh-Pasek, K, Michnick Golinkoff, R, Hollich, G. (1999). Trends and transitions in language development: Looking for the missing piece. *Developmental neuropsychology, 16*(2), 139-162.

Hollich, G. J., Hirsh-Pasek, K., Golinkoff, R. M., Brand, R. J., Brown, E., Chung, H. L., et al. (2000). Breaking the language barrier: an emergentist coalition model for the origins of word learning. *Monogr Soc Res Child Dev, 65*(3), i-vi, 1-123.

Houston, D. M., Carter, A. K., Pisoni, D. B., Kirk, K. I., Ying, E. A. (2005). Word Learning in Children Following Cochlear Implantation. *The Volta review, 105*(1), 41-72.

Houston, D. M., Miyamoto, R. T. (2010). Effects of early auditory experience on word learning and speech perception in deaf children with cochlear implants: implications for sensitive periods of language development. *Otology & neurotology: official publication of the American Otological Society, American Neurotology Society [and] European Academy of Otology and Neurotology, 31*(8), 1248.

Houston, D. M., Stewart, J., Moberly, A. C., Hollich, G., Miyamoto, R. T. (2012). Word learning in deaf children with cochlear implants: effects of early auditory experience. *Developmental science, 15*(3), 448-461. doi: 10.1111/j.1467-7687.2012.01140.x

Huttenlocher, J., Haight, W., Bryk, A., Seltzer, M., Lyons, T. (1991). Early vocabulary growth: relation to language input and gender. *Developmental psychology, 27*(2), 236.

Jacobs, E., Langereis, M. C., Frijns, J. H. M., Free, R. H., Goedegebure, A., Smits, C., et al. (2016). Benefits of simultaneous bilateral cochlear implantation on verbal reasoning skills in prelingually deaf children. *Research in Developmental Disabilities, 58*, 104-113. doi: https://doi.org/10.1016/j.ridd.2016.08.016

Jarosz, A. F., & Wiley, J. (2014). What are the odds? A practical guide to computing and reporting Bayes factors. The Journal of Problem Solving, 7, 2. https://doi.org/10.7771/1932-6246.1167

Jaswal, V. K., Markman, E. M. (2001). Learning proper and common names in inferential versus ostensive contexts. *Child Development, 72*, 768-786.

Jeffreys, H. (1961). The theory of probability. Oxford, United Kingdom: Oxford University Press.

Jung, K. H., Won, J. H., Drennan, W. R., Jameyson, E., Miyasaki, G., Norton, S. J., et al. (2012). Psychoacoustic performance and music and speech perception in prelingually deafened children with cochlear implants. *Audiology and Neurootology, 17*, 189-197.

Kirkpatrick, L., Feeney, B. (2013). *A simple guide to IBM SPSS statistics for version 20* (Student ed.). Belmont, Calif.: Wadsworth: Cengage Learning.

Kort, W., Schittekatte, M., Compaan, E. (2008). *CELF-4-NL: clinical evaluation of language fundamentals*. Amsterdam: Pearson Assessment and Information.

Kral, A., O'Donoghue, G. M. (2010). Profound Deafness in Childhood. *New England Journal of Medicine, 363*(15), 1438-1450. doi: 10.1056/NEJMra0911225

Kronenberger, W. G., Pisoni, D. B., Harris, M. S., Hoen, H. M., Xu, H., Miyamoto, R. T. (2013). Profiles of Verbal Working Memory Growth Predict Speech and Language Development in Children with Cochlear Implants. *Journal of Speech, Language, and Hearing Research 56*(3), 805-825. doi: 10.1044/1092-4388(2012/11-0356)

Ladefoged, P. (1993). *A course in phonetics*. New York: Harcourt Brace.

Levine, D., Strother-Garcia, K., Golinkoff, R. M., Hirsh-Pasek, K. (2016). Language Development in the First Year of Life: What Deaf Children Might Be Missing Before Cochlear Implantation. *Otology & Neurotology, 37*(2), e56-e62. doi: 10.1097/mao.0000000000000908

Lorenzi, C., Gilbert, G., Carn, H., Garnier, S., Moore, B. (2006). *Speech perception problems of the hearing impaired reflect inability to use temporal fine structure.* Paper presented at the Proceedings of the National Academy of Sciences USA.

Macken, M. A. (1979). Developmental reorganization of phonology: A hierarchy of basic units of acquisition. *Lingua, 49*(1), 11-49. doi: http://dx.doi.org/10.1016/0024-3841(79)90073-1

MacRoy-Higgins, M., Schwartz, R. G., Shafer, V. L., Marton, K. (2013). Influence of phonotactic probability/ neighbourhood density on lexical learning in late talkers. *International Journal of Language & Communication Disorders, 48*(2), 188-199.

Maïonchi-Pino, N., Cara, B. de, Écalle, J, Magnan, A. (2012). Are French dyslexic children sensitive to consonant sonority in segmentation strategies? Preliminary evidence from a letter detection task. *Res Dev Disabil, 33*(1), 12-23.

Markson, L., Bloom, P. (1997). Evidence against a dedicated system for word learning in children. *Nature, 385*(6619), 813-815. doi: 10.1038/385813a0

Miyamoto, R. T., Colson, B., Henning, S., Pisoni, D. (2017). Cochlear implantation in infants below 12 months of age. *World Journal of Otorhinolaryngology - Head and Neck Surgery, 3*(4), 214-218. doi: https://doi.org/10.1016/j.wjorl.2017.12.001

Nicholas, J. G., Geers, A. E. (2008). Expected test scores for preschoolers with a cochlear implant who use spoken language. *American Journal of Speech-Language Pathology, 17*(2), 121-138.

Niparko, J. K., Tobey, E. A., Thal, D. J., Eisenberg, L. S., Wang, N. Y., Quittner, A. L., et al. (2010). Spoken language development in children following cochlear implantation. *The Journal of the American Medical Association, 303*(15), 1498-1506. doi: 10.1001/jama.2010.451

Oktapoti, M., Okalidou, A., Kyriafinis, G., Petinou, K., Vital, V., Herman, R. (2016). Investigating use of a parent report tool to measure vocabulary development in deaf Greek-speaking children with cochlear implants. *Deafness & Education International*, *18*(1), 3-12.

Parker, S. (2008). Sound level protrusions as physical correlates of sonority. *J Phonetics*, *36*(1), 55-90.

Pimperton, H., Walker, E. A. (2018). Word Learning in Children With Cochlear Implants: Examining Performance Relative to Hearing Peers and Relations With Age at Implantation. *Ear and Hearing, 39*(5), 980-991. doi: 10.1097/aud.0000000000000560

Pisoni, D. B., Cleary, M. (2003). Measures of working memory span and verbal rehearsal speed in deaf children after cochlear implantation. *Ear and hearing, 24*(1 Suppl), 106S.

Pro, Cool Edit. (2003). Phoenix. *AZ: Syntrillium Software Corporation*.

Quittner, A. L., Cejas, I., Wang, N-Y., Niparko, J. K., Barker, D. H. (2016). Symbolic play and novel noun learning in deaf and hearing children: Longitudinal effects of access to sound on early precursors of language. *PloS one, 11*(5), e0155964.

Robertson, V. S., von Hapsburg, D., Hay, J. S. (2017). The Effect of Hearing Loss on Novel Word Learning in Infant- and Adult-Directed Speech. *Ear Hear*, *38*(6), 701-713. doi: 10.1097/aud.0000000000000455

Roland, J. T. Jr. , Cosetti , M., Wang, K. H., Immerman, S., Waltzman, S. B. (2009). Cochlear implantation in the very young child: longterm safety and efficacy. *Laryngoscope*, *119*, 2205-2210.

Schiller, N.O., Meyer, A. S., Baayen, R. H., Levelt, W. J. M. (1996). A Comparison of Lexeme and Speech Syllables in Dutch. *Journal of Quantitative Linguistics*, *3*(1), 8-28.

Schlichting, L. (2005). *Peabody Picture Vocabulary Test [3rd ed., Dutch Version (PPVT-IIINL)]*. Amsterdam: Amsterdam: Pearson Assessment and Information B.V.

Schwartz, R. G. (2015). The when and how of input frequency effects. *Journal of Child Language*, *42*(2), 298-300. doi: http://dx.doi.org/10.1017/S0305000914000671

See, R. L., Driscoll, V. D., Gfeller, K. (2013). Speech intonation and melodic contour recognition in children with cochlear implants and with normal hearing. *Otology & Neurotology*, *34*, 490.

Sievers, E. (1881). *Grundzüge der Phonetik*. Leipzig: Breitkopf und Hartel.

Sparreboom, M., Langereis, M. C., Snik, A. F. M., Mylanus, E. A. M. (2015). Long-term outcomes on spatial hearing, speech recognition and receptive vocabulary after sequential bilateral cochlear implantation in children. *Research in Developmental Disabilities*, *36*, 328-337. doi: https://doi.org/10.1016/j.ridd.2014.10.030

Spiegel, C., Halberda, J. (2011). Rapid fast-mapping abilities in 2-year-olds. *Journal of Experimental Child Psychology*, *109*, 132-140.

Stelmachowicz, P. G., Pittman, A. L., Hoover, B. M., Lewis, D. E. (2004). Novel-word learning in children with normal hearing and hearing loss. *Ear Hear*, *25*(1), 47-56. doi: 10.1097/01.aud.0000111258.98509.de

Storkel, H. L., Lee, S. Y. (2011). The independent effects of phonotactic probability and neighbourhood density on lexical acquisition by preschool children *Language and Cognitive Processes, 26*(2), 191-211. doi: 10.1080/01690961003787609

Talli, I., Okalidou, A., Tsalighopoulos, M. (2018). The relation between short-term memory and vocabulary skills in Greek children with cochlear implants: The role of hearing experience. *First Language*, 0142723717749073.

van Wieringen, A., Wouters, J. (2015). What can we expect of normally-developing children implanted at a young age with respect to their auditory, linguistic and cognitive skills? *Hearing Research*. doi: http://dx.doi.org/10.1016/j.heares.2014.09.002

Vihman, M. M. (2016). Learning words and learning sounds: Advances in language development. *Br J Psychol*. doi: 10.1111/bjop.12207

Walker, E. A., McGregor, K. K. (2013). Word learning processes in children with cochlear implants. *Journal of Speech, Language, and Hearing Research, 56*(2), 375-387.

Whitmal, N. A., 3rd, DeMaio, D., Lin, R. (2015). Effects of envelope bandwidth on importance functions for cochlear implant simulations. *The Journal of the Acoustical Society of America, 137*(2), 733-744. doi: 10.1121/1.4906260

Willstedt-Svensson, U., Lofqvist, A., Almqvist, B., Sahlen, B. (2004). Is age at implant the only factor that counts? The influence of working memory on lexical and grammatical development in children with cochlear implants. *Int J Audiol, 43*(9), 506-515.

Wilson, B. S. (2013). Toward better representations of sound with cochlear implants. *Nature medicine*, *19*(10), 1245.

Wilson, B. S. (2015). Getting a decent (but sparse) signal to the brain for users of cochlear implants. *Hearing research*, *322*, 24-38.

Wouters, J., Damman, W., Bosman, A. J. (1994). Vlaamse opname van woordenlijsten voor spraakaudiometrie. *Logopedie: informatiemedium van de Vlaamse vereniging voor logopedisten*, *7*, 28-34.

FIGURE LEGEND

Figure 1: Diagram summarizes the interactive processes involved in learning new words and building a lexicon, namely: fast mapping, retention and extension.

Figure 2: Diagram illustrating the PRAAT waveform, spectrogram, and intensity contour of CVC words of varying sonority components.

Figure 3: Flow chart of the sonority experiment trial. Pictures are of novel objects, obtained with author's permission from a previous study by MacRoy-Higgins et al. (2013).

Figure 4: PRAAT waveform, spectrogram, and intensity contour of the token /xar/ with demarcation of the phoneme boundaries and the sound peak minima of consonants.

Figure 5: Box plot comparing the median accuracy percent correct scores and interquartile ranges of the S-NWL in the 3 different experimental groups. No statistically significant differences between groups were detected according to Kruskal Wallis test at $p < 0.05$. Horizontal line indicates the chance level of performance. Different letters indicate significant differences between experimental groups according to pairwise comparison using Mann–Whitney *U* test at $p < 0.05$.

Figure 6: Cluster bar chart comparing the sonority accuracy percent correct score on the different sonority conditions within and across test groups. CI indicates cochlear implant; NHA, normal-hearing adults; NHC, normal-hearing children. No statistically significant differences between groups or within groups were detected according to Kruskal Wallis test, and Friedman one-way ANOVAs respectively, at $p < 0.05$.

Figure 7: Bar chart comparing the visual and sonority-related average reaction time in milliseconds (mean and SD) across the 3 groups. Different letters (a,b) across groups indicate statistically significant differences for the visual and the sonority task reaction times separately, according to post hoc tests with Bonferroni correction at $p < 0.05$. CI indicates cochlear implant; NHA, normal-hearing adults; NHC, normal-hearing children; RT, reaction time.

Figure 8: Cluster bar chart comparing the reaction time in milliseconds (mean and SD) on the different sonority conditions across test groups. Different letters (a,b) within each sonority condition indicate significant differences between experimental groups according to post hoc test with Bonferroni correction at $p < 0.05$. CI indicates cochlear implant; NHA, normal-hearing adults; NHC, normal-hearing children; RT, reaction time.

Figure 9: Bar chart comparing the PPVT and DST percentile score performance across children test groups. Different letters (a, b) indicate significant differences across groups according to an independent-samples *t* test at $p < 0.05$. CI indicates cochlear implant; DST, digit span test; NHC, normal-hearing children; PPVT; Peabody picture vocabulary test.

Figure 10: Scatter plots showing the correlation between (a) sonority NWL accuracy scores and PPVT raw scores (b) PPVT raw scores and DST raw scores for (1) NHC and (2) children with CIs. Statistically significant correlations ($p<0.05$) were detected in 1a, 1b and 2b.

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