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# Sonority's Effect as a Surface Cue on Lexical Speech Perception of Children with Cochlear Implants

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## ABSTRACT

**Objectives** Sonority is the relative perceptual prominence/loudness of speech sounds of the same length, stress, and pitch. Children with cochlear implants (CIs), with restored audibility and relatively intact temporal processing, are expected to benefit from the perceptual prominence cues of highly sonorous sounds. Sonority also influences lexical access through the sonority sequencing principle (SSP), a grammatical phonotactic rule, which facilitates the recognition and segmentation of syllables within speech. The more non-sonorous the onset of a syllable is, the larger is the degree of sonority rise to the nucleus, and the more optimal the SSP. Children with CIs may experience hindered or delayed development of the language learning rule SSP, as a result of their deprived/degraded auditory experience. The purpose of the study was to explore sonority's role in speech perception and lexical access of prelingually deafened children with CIs.

**Design** A case-control study with 15 children with CIs, 25 normal-hearing children and 50 normal-hearing adults was conducted, using a lexical identification task of novel, non-real CV-CV words taught via fast mapping. The CV-CV words were constructed according to four sonority conditions, entailing syllables with sonorous onsets/ less optimal SSP (SS) and non-sonorous onsets/ optimal SSP (NS) in all combinations, i.e. SS-SS, SS-NS, NS-SS and NS-NS. Outcome measures were accuracy and reaction times. A subgroup analysis of 12 children with CIs pair-matched to 12 normal-hearing children on hearing age aimed to study the effect of oral-language exposure period on the sonority-related performance.

**Results** The children groups showed similar accuracy performance, overall and across all the sonority conditions. However, within group comparisons showed that the children with CIs scored more accurately on the SS-SS condition relative to the NS-NS and NS-SS conditions, while the normal-hearing children performed equally well across all conditions. Additionally, adult-comparable accuracy performance was achieved by the children with CIs only on the SS-SS condition, as opposed to NS-SS, SS-NS and SS-SS conditions for normal-hearing children. Accuracy analysis of the subgroups of children matched in hearing age showed similar results. Overall longer reaction times were recorded by the children with CIs on the sonority-treated lexical task, specifically on the SS-SS condition compared to age-matched controls. However, the subgroup analysis showed that both groups of children did not differ on reaction times.

**Conclusions** Children with CIs performed better in lexical tasks relying on the sonority perceptual prominence cues, as in SS-SS condition, than on SSP-initial relying conditions as NS-NS and NS-SS. Template–driven word learning, an early word learning strategy, appears to play a role in the lexical access of children with CIs whether matched in hearing age or not. The SS-SS condition acts as a preferred word template. The longer reaction times brought about by the highly accurate SS-SS condition in children with CIs is possibly because listening becomes more effortful. The lack of reaction times difference between the children groups when matched on hearing age points out the importance of oral-language exposure period as a key factor in developing the auditory processing skills.

# INTRODUCTION

## Cochlear Implants and Speech Perception

Cochlear implantation has been gaining growing acceptance as an effective treatment for individuals with severe-to-profound sensorineural hearing loss. As a result, the number of pediatric cochlear implants (CIs) has been distinctly growing (Bradham & Jones 2008). According to the US National Institute of Health (2012), there are approximately 324,200 individuals with CIs worldwide. The benefits of CIs during the course of language acquisition have been documented for both speech perception and speech production (Fu & Galvin 2007; Shannon 2012).

Speech acoustic cues, including temporal-spectral ones, comprise the segmental (phonetic) features of the individual phonemes (Snow 2001). Individuals with CIs can demonstrate good word recognition accuracy; however it is unclear how they utilize the various acoustic cues to contribute to phonetic perception (Winn et al. 2011). Research efforts should be expanded to better recognize, identify and understand the way these cues are utilized in language processing, as this knowledge could guide the development and tailoring of better speech processing algorithms and rehabilitative tool outcomes (Jung et al. 2012; Sagi et al. 2009).

## Sonority and Sonority Sequencing Principle

Sonority (or vowel-likeness) is one of the phonetic/ phonological cues that facilitates the recognition and segmentation of syllables within speech (Ettlinger et al. 2012; Miozzo & Buchwald 2013), thereby aiding child language acquisition (Ohala & Kawasaki-Fukumori 1997; Pater 2009). Sonority by definition, is a scalar property of the relative loudness/ perceptual prominence of a particular sound segment compared to other sounds of the same length, stress, and pitch (Ladefoged 1993; Parker 2008). Sonority has been correlated to the openness of the vocal tract (Goldsmith 1990), with an underlying abstract language-specific phonetic representation (Beckman et al. 1992). Sonorous sounds include vowels, glides, liquids (flaps, laterals), and nasals, while non-sonorous sounds include obstruents (fricatives, affricates, and plosives) (Selkirk 1984). Sonority, being a perceptual aspect, is very difficult to quantify. Various scales have been proposed to order speech sounds on a sonority hierarchy. However, no universal sonority hierarchy exists, specifically when it comes to the ordering of obstruents (Parker 2008; Selkirk 1984; Steriade 1982), with claims of language-specific differences (Steriade 1982). According to Parker (2008) there are at least 98 different correlates of sonority, however very few attempts were made to instrumentally confirm them. Parker (2008) provided physical evidence supporting the sonority hierarchy. A partially new conceptualization of the physical realization of sonority was proposed, namely the sound level values at protrusions or extremes. These are values at the point of maximal and minimal intensity of vowels and consonants, respectively. Phonemes in English, Spanish, and Quechua were analyzed and the sonority intensity values were found to be strongly correlated ($r = 0.91$) with the typical phonological sonority hierarchy indices proposed. The study by Parker (2008) provided an empirical evidence that sonority is correlated with a measurable physical parameter.

The ability of speech sounds to follow one another in phonological strings of a language is defined by the phonotactic rules (Blevins 1995; Chomsky 1969; Jakobson 1968). Sonority plays a grammatical role in defining syllable structure through the language-universal phonotactic principle termed sonority sequencing principle (SSP) (Clements 1990; Selkirk 1984; Zec 1995). According to 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. This sonority-based principle thus determines the position of phonemes within the syllable, where sonority increases maximally and steadily from the onset to the vowel (Clements 1990). Therefore according to SSP, the more optimal the sonority sequencing is, the larger is the degree of sonority rise from the onset to the nucleus of the syllable.

The language-specific knowledge of phoneme co-occurrences affects word segmentation (McQueen 1998; Norris et al. 1997) and syllabification (Redford & Randall 2005; Smith & Pitt 1999; Treiman & Zukowski 1990). Sonority is one of the factors predicting the sequence ordering mastered by young children (Ohala & Kawasaki-Fukumori 1997; Pater 2009), and the rate and type of errors observed in individuals with developmental or acquired language impairments (Bastiaanse et al. 1994; Béland et al. 1990; Buckingham 1986; Christman 1994; Romani & Calabrese 1998; Romani & Galluzzi 2005; Romani et al. 2002; Stenneken et al. 2005). Studies have supported the role of SSP in adult speech perception (Berent et al. 2008; Berent et al. 2007), continuous speech segmentation (Ettlinger et al. 2012), and child language acquisition (Ohala & Kawasaki-Fukumori 1997; Pater 2009)

Several studies have tested the sonority related-grammatical markedness through assessing production and perception of SSP-violating onset clusters versus SSP-adhering ones in typically developing children including Greek, Dutch, English, Hebrew, and Norwegian language (Berent et al. 2011; Clements 1990; Ohala 1999; Syrika et al. 2011; Yavaş et al. 2008). It is widely debated whether the sonority related-grammatical markedness is innate or learned (Parker 2008). Infants as young as nine months of age have been shown to favor SSP- adhering syllables like “blif” over SSP-violating syllables like “lbif”, despite no experience with either (Friederici & Wessels 1993). However, the cumulative knowledge about SSP-adhering and violating structures in a language is suggested to be learnable, as demonstrated by the fact that each language has different phonotactics (Redford 2008) and also by experiments that tested the ability to learn novel phonotactic patterns over a set of data (Chambers et al. 2003; Dell et al. 2000; Onishi et al. 2002; Warker & Dell 2006).

Sonority, as one of the factors influencing word segmentation and the sequence ordering mastered by young children, is thus expected to play a role in the process of lexical access and acquisition, which is mediated by a fast-mapping strategy between the referent and lexical label.

## Lexical Access

A mental representation of a word must exist for the individual to be able to recognize it. In adults, acoustic spectra, among other cues of semantics, syntax and category, represent and provide access to the word in a speaker's lexicon. Lexical access in adults is facilitated by the representation of a word as a unique combination of small number of units (syllable, foot, mora) (Bertoncini & Mehler 1981). What children attend to in the process of lexical acquisition is not fully clear. Suggestions exist that during the first 6-12 months of life, infants utilize acoustic-phonetic mechanisms to store only stressed and word-initial syllables, as they find a way into the language system (Echols & Newport 1992; Gleitman & Wanner 1982). Later on, when the child has reached the understanding that words are used to name categories of objects and events, it adopts a holistic, less analytic approach in which semantic content rather than fine phonetic discrimination is of primary importance (Charles-Luce & Luce 1990; Ferguson & Farwell 1975; Hallé & de Boysson-Bardies 1994; Merriman & Schuster 1991). This whole-word processing starts around the period they have acquired 30 productive words and may last several years, as basic knowledge of words and related conceptual distinctions build up. Template-driven word learning is a form of whole-word processing, with a tendency for learning words with a particular prosodic frame. The word-template acts as a lexical generalization that later spurs further learning of words that fit into the same template (Macken 1979).

## Fast Mapping

Fast mapping is the capability of learning a word after minimal exposure to the new label. It develops during the period of whole-word learning (Jaswal & Markman 2001) and involves two essential processes; referent selection and referent retention. Referent selection is the process by which the child determines the correct referent of a novel label. Referent retention is the process of storage of this newly formed label–object mapping in the memory for later use. During natural conversation, children are exposed to novel words frequently, and therefore should be able to perform these tasks rapidly and repeatedly (Spiegel & Halberda 2011).

## Sonority Research in Individuals with CIs

Very few studies have investigated the role of sonority in speech of children with CIs. Chin and Finnegan (2002) examined variations in English complex onset realizations by children who use CIs. Results showed that one-segment realizations generally respected sonority principles, with the more sonorous segment being omitted and the less sonorous one retained. Kim and Chin (2008) investigated fortition and lenition patterns of error production in children with CIs. Fortition strengthens consonant articulation, that is, it makes the consonants less sonorous, while lenition weakens consonant articulation, thereby it makes the consonants more sonorous (Brandão de Carvalho et al. 2008). Data supported that lenition errors reflect the minimization of articulatory effort in specific phonological contexts, while fortition errors are pervasive and not context-sensitive in the same way that lenition errors are. The resulting pattern was consistent with early phonological stage patterns of normal-hearing children, and suggested that phonological development in the two groups reflects a single universal acquisition pattern based on markedness. However, both studies investigated the role of sonority on speech production, rather than on speech perception and lexical access.

## Study Rationale, Hypothesis, and Objectives

For CI users, temporal processing can be as good as that of normal-hearing listeners, as evidenced by temporal modulation transfer functions (Shannon 1992) and gap detection tasks (Shannon 1989). Thus, children with CIs are expected to detect the perceptual prominence cues provided by the sonority contour of highly sonorous consonants, equivalent to their age-matched normal-hearing children (NHC). Sonority also influences lexical processing through the phonological grammar rule of SSP. Sonority sequencing principle, being a language learning rule, is expected to be delayed or hindered in children with CIs as a result of the earlier period of auditory deprivation and the relatively degraded auditory signal provided by CIs. Furthermore, children with CIs may shift to rely on the more accessible cue of sonority perceptual prominence as a compensatory strategy. Therefore, we hypothesize that children with CIs and normal-hearing peers differ in terms of lexical access performance.

The goal of the current study was to explore the role of sonority in terms of the perceptual prominence cues versus SSP cues in the lexical access of prelingually deafened children with CIs. The current research addressed the following questions: 1- How do the sonority related parameters affect the degree of lexical perception in children with CIs, relative to normal-hearing NHC and normal-hearing adults (NHA)? 2- Do children with CIs perform better in lexical tasks by relying on perceptual prominence cues brought about by highly sonorous lexical segments or do they rely on language learning rules evidenced by sonority sequencing cues? 3- Do NHC perform differently on sonority-driven perceptual prominence cues versus language dependent cues, and is their performance comparable to NHA? 4- Do children with CIs vary in lexical access strategies relative to their normal-hearing peers, being exposed to periods of relative auditory deprivation and relatively degraded auditory signal input?

# METHODS

## Participants

A Case-Control study was conducted including three groups of Greek-speaking participants; 15 children with CIs, 25 NHC and 50 NHA. The sample size of children with CIs was guided by the availability of children complying with the inclusion criteria. Larger sample sizes were included for the normal-hearing groups, as they are of easier access, to provide reference data for performance in NHA and NHC. Power analysis was not possible as the predicted outcome value was unknown.

Children with CIs included in the current study were prelingually deaf, as defined by an age of implantation of maximally 3 years. A postimplant age of at least two years was set to ensure that participants had some experience with spoken language and were able to perform the task under test using the fast mapping procedure. Additionally they had to be monolingual, with normal nonverbal Intelligence Quotient (NVIQ), and no additional disabilities. Proper audibility/functionality of the CI device with recent mapping within the last six months was also set within the inclusion criteria. All of the children with CIs were unilateral users. The age and postimplant age of each of the children with CIs are depicted in Table 1. The NHC were matched to the children with CIs based on the chronological age range, and gender. Inclusion criteria for the typically developing (TD) NHC included normal hearing, normal NVIQ, and age-appropriate speech and language skills. The NHA were matched on the basis of gender to the two groups of children. Inclusion criteria for NHA included normal hearing, with age limit set at 40 years to avoid potential memory influences on the fast mapping referent retention process. Inclusion criteria was employed by the referring audiologist, and further validated through a set of pretest interview questions administered by the first author to the attending parent.

Informed Consents were obtained from all the participants above 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 AHEPA hospital/Thessaloniki and by the Special Committee of Research Ethics of UOM/Thessaloniki.

## Materials

A battery of tests was selected including the sonority experiment, audiological, speech and language tests, as described in the next section. Audiological tests included oto-acoustic emissions and pure tone audiometry to ensure normal hearing of the control groups. Moreover, for children with CIs, in free field, pure tone average (PTA) thresholds were at least 25 dB HL to ensure proper functionality of the CI device. In addition, speech audiometry tests were done to document the speech recognition abilities of the children with CIs. Aided free-field pure-tone average thresholds (500 Hz-2 kHz), and speech audiometry correct percent scores (word and sentence) of the children with CIs are depicted in Table 1. Raven IQ test (Raven et al. 2000, updated 2004) was employed to ensure normal NVIQ using the available Greek norms for the children aged up to 11 ; 11. Three NHC and two children with CIs, outside the current sample of 25 NHC and 15 children with CIs, who scored at or below the 10$^{th}$ percentile (Grade of IV- and

V), were excluded. For older children, attendance of mainstream schools with at least medium academic achievement was used as an indicator of normal NVIQ. A protocol of receptive vocabulary in Greek was used to compare the receptive language scores of both children groups, and to ensure that the NHC were TD using the Greek norms up to the age of 6 ; 11. Attendance of mainstream schools with at least medium academic achievement was used as an indicator of TD language in NHC with age 7; and higher. The Test of Articulatory and Phonological Development (PAL 1995) was used to compare qualitatively the phonological skills of both children groups, and to ensure that the NHC are TD. The battery of test took 50 minutes on average depending on the child's age and responsiveness.

In addition, a novel fast mapping experiment was designed to test the hypothesis of the sonority-related lexical perception.

## Sonority Experiment

### Sonority-Related Experiment Design

The Sonority Experiment was a computer-based, lexical identification task of newly-learned CV-CV words. The CV-CV words were labels of funny objects learned via fast mapping procedures. E-Prime 2.0 Professional software (Psychology Software Tools Inc 2012) was used to build the experiment. Audio stimuli included 16 disyllabic, novel, non-real CV-CV words with a trochaic prosodic structure within four sonority conditions. Funny objects were selected as pictures, obtained with author’s permission from a previous study by MacRoy-Higgins et al. (2013).

## Sonority-Related Experiment Procedure

Figure 1 illustrates the procedure for one trial, which is repeated for all of the 16 trials of the experiment. Each trial consisted of a pair of CV-CV words of opposing sonority conditions, as explained in the following section. The fast mapping (Spiegel & Halberda 2011) procedure was used to familiarize the funny 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 millisecond (msec), to ensure that identification was based on presentation of discrete trials. The insertion of a foil within the identification slide was guided by the pilot study (Hamza et al. 2016) where the two picture array's chance level was relatively high (79.16% at $p < 0.05$), while that of the three picture array format was 52.75% at ($p < 0.05$). Both accuracy measures and reaction times (RTs) (from the offset of the target-word audio) were recorded and logged through the touch screen.

## Sonority-Related Experiment Test Setting

Testing took place at AHEPA Audiology Clinic sound treated room. A story scenario was developed to instruct the children. A practice session including six trials (two with real object words and four with novel words) was employed before testing. A pass score criteria of 50% in the trial session was mandatory before moving on to the testing. Hand position was standardized using a palm-shaped pad, with versions customized for left- and right-handed participants. Audios were played through two loudspeakers placed at 45 degree Azimuth calibrated at 70 dB HL at 70 cm from seating position. Testing session lasted 20 minutes including the practice.

## Sonority-Related Experiment Stimuli

According to the sonority hierarchy, vowels (V) within the CV-CV novel words are always sonorous (S), consonants (C) could be sonorous (S) or non-sonorous (N). The test stimuli building blocks of words were thus sonorous syllables (SS) and non-sonorous syllables (NS). The SS syllable is perceptually-prominent as it is composed of two sonorous phonemes, and has a less optimal SSP as it has a relatively smaller degree of sonority rise from the onset to the peak of nucleus. The NS syllable exhibits the opposite profile where it has a more optimal SSP as a result of the larger degree of sonority rise from onset to peak, and a less perceptually-prominent sonority contour caused by the non-sonorous consonant. This yields four possible sonority testing conditions at a lexical level; NS-NS, NS-SS, SS-NS, and SS-SS. At a word level there are three hierarchies within the sonority conditions. The NS-NS condition has low sonority perceptual prominence and an optimal SSP, NS-SS and SS-NS have medium sonority contour perceptual prominence and mid-optimal SSP profile, while SS-SS has a high sonority contour perceptual prominence and a least optimal SSP profile. The mid-hierarchy classes allow for studying the interaction of sonority with syllable position: first vs second. Four different tokens, containing different consonants and vowels, were generated per sonority condition, yielding the 16 different novel word stimuli (4 conditions x 4 tokens). Sonorous onset consonants included flaps, laterals, and nasals. The Greek language lacks glides (Mennen & Okalidou 2007). Non-sonorous onset consonants included voiced and voiceless fricatives, voiced and voiceless stops (Parker 2008; Selkirk 1984). The current study did not include affricates, as many sonority scales ignore this class entirely, because of their inherent complications to classify as a single phoneme or cluster (Escure 1977; Hankamer & Aissen 1974; Lavoie 2001). Refer to Table 2 for an inventory of the sonority experiment stimuli, the sonority condition and phonemic content.

Phonotactic probability, the likelihood of occurrence of a sound sequence, facilitates spoken word recognition and production. The more common sound sequences are, the more accurately and/or faster they are recognized (Storkel & Lee 2011). In the current study, the frequency of occurrence of the CV syllables of the word stimuli was controlled for by matching them to a medium frequency of occurrence in the Greek language, with respect to syllable position. The frequencies of occurrence of syllables in Greek were calculated from a database (Adamidou et al. 2013) of the 20000 most frequent lemmas in Greek (consult Supplemental Digital Content 1.doc for the detailed procedure of calculation and matching). Novel words did not contain phonemes with the same place of articulation and manner to avoid confounding effects in perception due to syllabic similarity. The sonorous phonemic classes: flaps, laterals, and nasals were represented unevenly in the first vs. second position, due to the fact that there are only three classes versus 8 presentations of the sonorous class in each position. The choice of phoneme class representation in different positions was guided by an effort to counterbalance language bias frequency effects towards syllable position in the Greek language. The CV-CV stimuli were then paired into eight pairs of opposing sonority conditions, with creation of all possible pairing combinations.

Each novel word was randomly assigned to the picture of a funny object within the 8 pairs. Each of the 8 pairs was presented twice with alterations of the target word through a random process. Four different versions of the novel word- picture assignment, trial order, target word order and picture position were created. Choice of the test version administered to the participant was through systematic random assignment.

## Acoustical Analyses of the Stimuli for the Sonority Experiment

Novel word stimuli as well as carrier phrases were recorded by a native Greek female speaker using Sony PCMD100 Portable High Resolution Audio Recorder in a sound treated booth. The carrier phrase and the target word were collated via Sony Sound Forge Pro10.0. Then the collated phrases were normalized to a peak level of 80 dB HL on Gold wave (GoldWaveInc 2015) to ensure that the results under test were not due to differences in presentation intensity. The mean intensity output was measured for each sonority condition using PRAAT (Boersma & Weenink 2016). For NS-NS the mean intensity +/- SD was 70.5 dB +/- 3.1 dB, for NS-SS was 71 dB +/- 1.6 dB, for SS-NS was 69.4 dB+/- 1.7 dB, and for SS-SS was 70.6 dB +/- 1.1 dB.

Acoustic analyses of the stimuli were conducted using Parker (2008) methodology to provide a physical correlate of the sonority classes of non-sonorous vs. sonorous consonant components. For this the sound minima peak intensity value was determined for the various consonants in the sonority classes with respect to syllable position (consult Supplemental Digital Content 2.doc for the detailed procedure of measurement). Figure 2 illustrates the token “vamo” as an example for the measurements performed on PRAAT. Table 3 illustrates the intensity minima values recorded for the various phonemes in the CV-CV word stimuli. An independent-samples $t$ test showed that the dB minimum value of the sonorous consonants were statistically higher than the non-sonorous consonants in the first position [$t(8.024) = 4.516$, $p=0.002$] and the second position [$t(9.053) = 7.344$, $p<0.001$]. Furthermore, four real Greek words that were recorded by the same speaker and used in the training phase were analyzed using the same Parker (2008) methodology on PRAAT. Table 4 shows that similar sonority measurement patterns were observed for the Greek real words as for the novel word stimuli.

### Visual Reaction Time Experiment

A nonverbal, visual task was added, as a control condition, to ensure that the process of picture selection had no influence on the RT results. Absence of RT differences between groups on the visual task excludes generic motor differences in the process of picture selection between the two groups. This will allow for conclusions to be drawn upon the actual impact of the auditory component of the sonority experiment.

The Visual localization experiment was run after the sonority experiment within the same session. The task involved a rabbit appearing on the screen in one of the three picture positions and the child was instructed to catch the rabbit as quickly as possible by touching the screen in the same manner as in the sonority experiment. Then the child would return his hand to the palm shaped pad and when ready, the procedure was repeated again for a total of eight trials. The RT was measured from the onset of appearance of the rabbit on the screen until the touch of it. The quickest visual RT of all eight trials was taken as the outcome measure.

### Data Analyses

The two major outcome performance measures of the sonority experiment were accuracy and RTs. Accuracy was expressed in percent correct score and RT was expressed in msec. The upper weight in performance judgment was given to accuracy, 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 first author, were removed from the data set. The percent of trials eliminated from the RT data set was 3.25% for NHA, 9.5% for NHC, and 15.8% for children with CIs. An alpha level of 0.05 was used for all statistical tests.

The accuracy percentage scores in the sonority-treated lexical perception task were not normally distributed even after log 10 transformation. Therefore, non-parametric 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 if pairwise comparisons were required. For within group comparisons the Friedman one way ANOVAs was applied, followed by Wilcoxon test if pairwise comparisons were required.

The visual task RT was normally distributed and so between group comparisons were performed using one-way ANOVA, with post hoc tests using the Bonferroni correction for multiple comparisons. The sonority experiment RT data were log10 transformed in order to achieve normality and, homoscedasticity of model's residuals before being analyzed via Mixed Linear Models using the ANOVA method. Due to the hierarchical nature of the data, the model involved a "between subject factor" (factor "Group", with three levels: NHA, NHC, and CI) and two "within subjects factors" with repeated measures (factor "Sonority Condition", with 4 levels: [NS-NS, NS-SS, SS-NS, SS-SS], and factor "Token.RT" with four levels nested within the levels of Sonority Condition). In the proposed model the subjects were considered a random effect factor nested within the three groups. Pairwise comparisons of mean values were performed by means of posthoc tests using the Bonferroni correction for multiple comparisons. For conceptual reasons, RT data are reported at the untransformed raw values.

A subgroup analysis was performed based on 12 children with CIs which were pair matched with 12 NHC according to the hearing/ oral-language exposure period. The oral-language exposure period was defined as the postimplant age in the children with CIs and the chronological age for the NHC. This analysis was carried out to study the effect of the oral-language exposure period on the performance of children with CIs, relative to NHC on the sonority task. As for the full sample analysis, the accuracy percentage scores were not normally distributed even after log 10 transformation. Therefore, non-parametric tests were applied to the raw untransformed data. For between group comparison Kruskal Wallis test was used for main effects, followed by Mann-Whitney *U* test if pairwise comparisons were required. For within group comparisons Friedman one way ANOVAs were used, followed by Wilcoxon test if pairwise comparisons were required. Both the visual RT and sonority RT data were normally distributed. An independent-samples *t* test analysis was used for between group comparisons.

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

# RESULTS

## Demographics

The mean age of the two children groups was not found to be statistically different, as shown by an independent-samples *t* test [t (38) = 0.494, p = 0.624]. Chi-square test of independence showed that all the studied groups had statistically similar distributions for gender (chi-square test of independence, $X^2 = 0.142$, df = 1, p = 0.931). Table 5 shows the age and gender distribution of the different groups. An independent-samples *t* test comparison of the Raven NVIQ test scores of the two children groups showed statistically similar performance [t (37) = 0.488, p = 0.628]. However, on the receptive vocabulary test, statistically significantly higher scores were obtained by the NHC relative to the children with CIs using an independent-samples *t* test [t (37) = 5.267, p < 0.01], as shown in Figure 3. Chi-square test of independence showed that the group of children with CIs entailed a statistically significantly higher number of children with non-age appropriate articulation relative to the NHC (chi-square test of independence, $X^2 = 16.501$, $df = 1$, $p < 0.01$).

All NHC were TD as validated through the normal hearing thresholds at all frequencies, normal NVIQ through Raven NVIQ scores or School report, normal receptive vocabulary scores or School report, and age appropriate phonological development on Articulation test assessed by Speech-Language Pathologist.

**Overall Accuracy Performance on Sonority-treated Lexical perception Task**

The accuracy performance on the sonority-treated lexical perception task ranged between 93.75% - 100% for the NHA group, 68.75% - 100% for the NHC group and 62.5% - 100% for the children with CIs group. Median accuracy percentage performance was 100% for both normal-hearing groups, whereas it was 93.75% for children with a CI. Kruskal Wallis analysis showed a statistically significant main effect of 'groups' on the overall accuracy performance ($p < 0.001$). Pairwise comparison using Mann-Whitney *U* test showed that the NHA scored statistically significantly more accurately than both the NHC ($U = 409$, $df = 74$, $p = 0.002$)] and children with CIs ($U = 150$, $df = 59$, $p < 0.001$)]. Yet, both groups of children did not score statistically different ($U = 140.5$, $df = 39$, $p = 0.167$), as illustrated in Figure 4. The more accurate performance of adults relative to the children groups, but not between age-matched children groups reflects underlying age-related developmental cognitive and language acquisition processes. A positive correlation between the sonority experiment lexical identification accuracy score and the receptive vocabulary score for the entire children sample, was shown $r = 0.53$, $p < 0.001$. That is, the higher the receptive score the better the performance on the lexical identification task, or vice versa.

**Group Accuracy Performance on Different Sonority Conditions**

Within group comparisons using Friedman one way ANOVAs showed that there was no main effect of the sonority condition on accuracy performance for the normal-hearing groups whether adults ($\chi2(49) = 1.714$, $p = 0.634$) or children ($\chi2(24) = 3.102$, $p = 0.376$). However, for the children with CIs a main effect of the sonority condition on accuracy performance was detected ($\chi2(14) = 8.711$, $p = 0.033$). Further Pairwise comparison using Wilcoxon test showed that the children with CIs scored statistically significantly higher on the SS-SS condition, a condition relying on perceptual prominence, relative to conditions starting with a non-sonorous (NS) syllable, namely NS-NS ($Z = -2.111$, $p = 0.035$) and NS-SS ($Z = -2.714$, $p = 0.007$). All children with CIs scored 100% correct on the SS-SS condition apart from subject 3, a 5 year old child, with a postimplant age of 3; 1 who scored 75%.

Across group comparisons, Kruskal Wallis analyses showed a main effect of the different experimental groups on the accuracy performance for NS-NS ($p = 0.002$), NS-SS ($p < 0.001$), and SS-NS ($p = 0.027$) conditions, but not for the SS-SS condition ($p = 0.179$). Pairwise comparison using Mann-Whitney *U* test showed that for NS-NS condition the NHA scored statistically significantly more accurately than both groups of children [NHC ($U = 496$, $df = 74$, $p = 0.018$, CI ($U = 228$, $df = 59$, $p < 0.001$)], while both groups of children scored statistically similar ($U=156$, $df=39$, $p=0.294$). For NS-SS and SS-NS conditions, the NHA scored statistically more accurately than the children with CIs [NS-SS ($U = 201$, $df = 64$, $p < 0.001$), SS-NS ($U = 287$, $df = 64$, $p = 0.006$)], and statistically similar to the NHC [NS-SS ($U = 523$, $df = 74$, $p = 0.052$), SS-NS ($U = 574$, $df = 74$, $p = 0.185$)]. Both children groups scored statistically similar on the medium sonority conditions [NS-SS ($U = 130.5$, $df = 39$, $p = 0.112$), SS-NS ($U = 157$, df

= 39, $p = 0.406$)]. Group performance within and across the different sonority conditions are shown in Figure 5.

**Group Reaction Time Performance**

Analysis of the RTs on the rabbit-visual task experiment using one-way ANOVA showed a statistically significant main effect of the test groups on the RT [$F(2, 87) = 7.614$, $p = 0.001$]. Post hoc tests with Bonferroni correction for multiple comparisons revealed that the adult group had statistically significantly faster RTs for the visual task (M = 517 msec, SD = 73 msec) relative to both groups of children [NHC (M = 589 msec, SD = 103 msec, $p = 0.002$); CIs (M = 583 msec, SD = 87 msec, $p = 0.029$)]. However, more importantly, the visual task's RTs of the children groups did not differ statistically from each other ($p=1.000$). This is important, as potential RT differences on the sonority audio-visual task between the children groups could be attributed to the auditory component rather than to the generic psychomotor ability to respond to the visual component. Group performances on the visual task are depicted in Figure 6.

With regard to the average RT on the sonority-treated lexical perception task, the analysis via Mixed Linear Models indicated a statistically significant main effect of Group on the average RT [$F(2, 89) = 23.397$, $p < 0.001$, $\eta 2 = 0.345$]. Post hoc analysis with Bonferroni correction for multiple comparisons showed that the normally-hearing adults (M = 500 msec, SD = 292 msec) yielded statistically significantly faster RTs than both groups of children [NHC (M = 902 msec, SD = 712 msec, $p < 0.001$), CIs (M = 1065 msec, SD = 838 msec, $p < 0.001$)]. This pattern on the audio-visual sonority task is similar to the visual-only task, suggesting that differences in the overall sonority RT between adults and children result at least partially from generic motor effects. The RT on the sonority-treated lexical perception task of the children with normal-hearing was statistically significantly faster than that of the group of children with CIs (p <

0.001). As indicated previously, there were no RT differences between the children groups on the rabbit-visual task. Thus the RT differences between the children groups on the sonority-treated lexical perception task are attributed to the processing load brought by the auditory/verbal component. In other words, the normally-hearing children processed the auditory/verbal stimuli faster than children with CIs.

Within the methodological frame of Mixed Linear Models there was no main effect of sonority on the RT [$F (3, 346) = 2.13$, $p = 0.096$, $\eta2 = 0.018$]. Additionally, there was no interaction between group and sonority condition [$F (6, 328) = 1.2$, $p = 0.306$, $\eta2 = 0.022$]. However, due to the statistically significant main effect of Group on the average RT, further exploration was carried out to define any specific sonority conditions by which the groups varied in their Sonority RT. Post hoc tests with Bonferroni corrections showed that the NHA [NSNS (M = 500 msec, SD = 31 msec), NS-SS (M = 527 msec, SD = 32 msec), SS-NS, (M = 495 msec, SD = 32 msec), SS-SS (M = 480 msec, SD = 31 msec)] were statistically significantly faster on all conditions than both groups of children [NHC: (NSNS: M = 897 msec, SD = 48 msec, $p < 0.001$), (NS-SS: M = 933 msec, SD = 47 msec, $p < 0.001$), (SS-NS: M = 1095 msec, SD = 47 msec, $p < 0.001$), (SS-SS: M = 821 msec, SD = 48 msec, $p < 0.001$); CIs (NSNS: M = 1163 msec, SD = 67 msec, $p < 0.001$), (NS-SS: M = 1028 msec, SD = 69 msec, $p < 0.001$), (SS-NS: M = 1076 msec, SD = 70 msec, $p < 0.001$), (SS-SS: M = 1114 msec, SD = 60 msec, $p < 0.001$)]. Comparison between the children groups showed that NHC had statistically similar RTs as the children with CIs on all sonority conditions [NSNS ($p = 0.087$), NS-SS ($p = 0.382$), SS-NS ($p = 0.216$)] except for the condition SS-SS ($p = 0.015$), where the children with the CIs were statistically significantly slower than the NHC. Even though children with CIs showed equivalent accuracy on SS-SS condition to not only the NHC but also to the adults, a statistically longer RT was needed by them, in order to achieve such high levels of accuracy on SS-SS condition. Reaction time on the different sonority conditions, across the experimental groups is shown in Figure 7.

**Token Analysis**

Token analysis was carried out to ensure that the hypothesis under test was not driven about by the effect of a specific token within a sonority condition. For each of the test group's sonority conditions, the four tokens within yielded statistically similar accuracy scores according to Mcnemar test with Bonferroni corrections for multiple comparisons. Across groups comparison of individual token accuracy scores using Chi-square test of independence showed no statistically significant differences between the three groups for any of the 16 tokens, after Bonferroni corrections for multiple comparisons. This rules out that the sonority condition's accuracy results were driven by a single token effect.

Analysis of the token's RT within the methodological frame of Mixed Linear Models using the ANOVA method showed a statistically significant interaction of tokens nested within the sonority conditions and the test groups (Condition x Token x Group) ($F = 1.784$, $df = 24$, $p = 0.012$). Post hoc tests with Bonferroni corrections for multiple comparisons showed that the token "mola" was the sole token within the SS-SS sonority condition with statistically significantly longer RTs for the children with CIs ($M = 1375$ msec, $SD = 1138$ msec) relative to the NHC ($M = 772$ msec, $SD = 560$ msec). This means that the RT of the SS-SS condition could have been driven by this single token. However, it is worth mentioning that, two of the remaining three tokens within the SS-SS condition were also of longer RT in the children with CIs relative to the NHC, yet not statistically significant.

**Subgroup Analysis**

Twelve children with CIs were pair matched with 12 NHC according to the oral-language exposure period. This analysis was carried out to study the effect of the oral-language exposure period on the performance of children with CIs on the different sonority conditions, and further probe the possible causes for the difference in the performance between the two groups of children.

The oral-language exposure period ranged from 3 ; 2 – 12 ; 8 (M = 7 ; 10 years, SD = 3;2 years) for children with CIs and 3 ; 8 – 13 ; 6 (M = 7 ; 9 years, SD = 3 ; 1 years) for NHC. The chronological age ranged from 6 ; 1 – 15 ; 2 (M = 10 ; 10 years, SD = 3 ; 3 years) for children with CIs and 3 ; 9 – 13 ; 6 (M= 7;11 years, SD = 3;3 years) for NHC. An independent-samples *t* test showed that the subgroups did not differ statistically according to the chronological age [t (22) = 1.701, p = 0.103]. An independent-samples *t* test comparison of the receptive vocabulary test scores continued to show a statistically significantly [t (21) = 2.814, p = 0.01] higher performance for the NHC (M = 103 score points, SD = 35 score points) relative to the children with CIs (M = 69 score points, SD = 22 score points). Additionally, Chi-square test of independence showed that the subgroup of children with CIs also entailed statistically significantly higher number of children with non-age appropriate articulation relative to the NHC (chi-square test of independence, $X^2 = 7.659$, df = 1, p = 0.01). A pattern similar to the one obtained in the chronological age sample analysis, despite the older chronological age of the children with CIs in the subgroup analysis.

The accuracy percentage performance on the sonority-treated lexical perception task ranged between 69.9%- 100% for the NHC subgroup, and 83%-100% for the children with CIs subgroup. Median accuracy percentage performance was 91% for the NHC subgroup and 94% for the children with CIs. Pairwise comparison using Mann-Whitney test showed that both subgroups of children did not score statistically significantly different (U = 61, df = 23, p = 0.507) on the sonority-treated lexical perception task, as is illustrated in Figure 8. This result is similar to the one obtained from chronological age sample analysis.

Within group comparisons showed no main effect of the sonority condition on accuracy performance for the NHC subgroup, and a statistically significant effect of sonority condition on the accuracy performance (χ2 (3) = 9.109, p = 0.028) for the children with CIs. Further Pairwise comparison using Wilcoxon test showed statistically significantly higher performance in SS-SS condition relative to NS-NS condition (Z = -2.236, p = 0.025) and NS-SS condition (Z = -2.121, p = 0.034) in children with CIs subgroup. Once again this result is similar to the one obtained from chronological age sample analysis.

Across group comparisons showed no statistically significant differences in the performance between both children subgroups on any of the sonority conditions [NS-NS (U = 72, df = 23, p = 1.000)], NS-SS (U = 62.5, df = 23, p = 0.506)], SS-NS (U = 65.5, df = 23, p = 0.514), SS-SS (U = 54, df = 23, p = 0.07)]. This result is also similar to the one obtained from chronological age sample analysis. It is worth noting that the children with CIs appear to score with extreme high accuracy on the SS-SS condition when matched according to the oral-language exposure period. All children within the CIs subgroup scored 100% percent correctly here, compared to 75% of the normal-hearing subgroup of children. Subgroup performance within and across the different sonority conditions is shown in Figure 9.

There were no statistically significant differences between the two children groups on the RT of the rabbit-visual task [t (14.333) = 1.459, p = 0.159], and on the sonority-treated lexical perception task [t (22) = 0.137, p = 0.892], as depicted in Figure 10. These results are different from the results obtained when comparing children groups of chronological age, where the children with the CIs were statistically significantly slower than the NHC as an overall and on SS-SS condition. Further exploration of the RT on the different sonority conditions using independent-samples *t* tests confirmed that both subgroups did not differ in RTs across the different sonority conditions [NS-NS [t (16.157) = 0.507, p = 0.619], NS-SS [t (22) = -0.281, p = 0.789], SS-NS [t (17.787) = 0.248, p = 0.807], even for the condition SS-SS [t (14.333) = 0.038, p = 0.970]. The RT on the different sonority conditions across the children subgroups is shown in Figure 11.

## DISCUSSION

Sonority, as a phonetic/phonological cue, is relatively understudied in the population of children with CIs. Previous research has focused on studying the production of SSP-violating stimuli, rather than on studying the influential effect of sonority on speech perception and lexical access of children with CIs. To our knowledge, there are no studies that have evaluated the role of sonority on lexical perception and access of phonotactically-legal sequences in prelingually deafened children with CIs. In the current study, the various sonority conditions; NS-NS, NS-SS, SS-NS, and SS-SS were studied to explore the interactive effect of sonority's perceptual prominence versus SSP on the degree of lexical access, while probing for the possible underlying processing and language mechanisms that influence lexical access in children with CIs.

The high overall accuracy scores observed in the current study by all groups was expected, since individuals in the study had a minimum hearing age of 2 years. According to Carey and Bartlett (1978) the fast mapping of words onto meanings is achieved during that age period, with a capability of acquiring words at a very rapid rate, on the order of 10 to 20 new words a day.

The following research questions were addressed in the current study with an ultimate goal to provide knowledge that can be used in optimizing auditory input access and improving learning strategies for children with CIs.

**Research Question 1- How do sonority-related parameters affect the degree of lexical perception in children with CIs, relative to NHC and NHA?**

In the current study, children with CIs performed as accurately as the NHC on each of the sonority conditions and as an overall score. Winn et al. (2011) has highlighted that under conditions of normal redundancy of acoustic cues, individuals with CIs could potentially achieve equally accurate performance on speech recognition tasks as the normal-hearing individuals. However, more importantly, CI users most probably use different acoustic cues to achieve such equally accurate performance. Pattern differences were observed when comparing the performance of each of the children groups to those of adults. Children with CIs performed adult-comparable "only" on the highly sonorous SS-SS condition, while the NHC scored equally well to NHA on all conditions apart from the NS-NS condition. This demonstrates that children with CIs were able to learn and identify words relying on perceptual prominence cues of highly sonorous segments with high, adult-equivalent accuracy.

In terms of RTs, a statistically significantly longer RT on SS-SS condition was required by the children with CIs relative to the NHC. A possible explanation is that the hearing impaired individual must invest extra effort to achieve perceptual success (Baddeley 1996; Pichora-Fuller etal. 2016). This comes at the expense of processing resources that could have been available for encoding the speech content in memory. However, a token effect was not ruled out for this SS-SS condition, meaning that the longer RT maybe also attributable to the specific token “mola”. Yet, two out of the three other tokens within the SS-SS condition showed also longer RT.

The answer to the first research question is therefore: both groups of children perform equally accurate on the lexical perception task as an overall and on the different sonority-related parameters. Differences in performance are detected when comparing both groups to the adult group, where the children with CIs show adult- equivalent accuracy on the SS-SS condition only. This higher accuracy performance on perceptually prominent lexical segments comes at the expense of processing resources as expressed by the longer RTs.

**Research Question 2- Do children with CIs perform better in lexical tasks by relying on perceptual prominence cues brought about by highly sonorous lexical segments or do they rely on language learning rules evidenced by sonority sequencing cues?**

The first research question showed that children groups performed equally accurate on the different sonority conditions. However, they may utilize cues in a different manner to achieve such equally accurate performance. This has been demonstrated through the within group comparison where an effect of the sonority-related parameters on the degree of lexical perception of children with CIs was demonstrated. Within group comparisons showed that children with CIs were able to learn and identify words relying on perceptual prominence cues of highly sonorous segments with high accuracy. This was evidenced through their statistically more accurate performance on SS-SS condition relative to the optimal-SSP onset syllable conditions (NS-NS and NS-SS). On the other hand, the NHC performed equally well on all conditions regardless of the sonority of the speech signal.

The consistent superior accuracy performance on the sonority condition SS-SS in children with CIs is evident through the within group comparison, as well as the adult comparable performance on that condition solely. Sonority influences speech perception through the perceptual prominence cues, as well as through the language learning rule of SSP. According to the auditory sensitivity hypothesis (Sussman 1993, 2001) the relatively immature auditory system of younger children, in terms of anatomical and neurological structures, is responsible for children relying more on louder, longer duration cues (Ohde & Haley 1997; Sussman 2001). In children with CIs, the reduced auditory sensitivity may cause them to display this pattern of immaturity even at an older age. This causes them to rely on louder cues, which explains the high accuracy on the SS-SS word template. Thus children with CIs were expected to detect the cues provided by the perceptual prominence of highly sonorous segments, given that they have restored audibility through the CIs, and are documented to have intact temporal processing (Shannon 1989, 1992). On the other hand, their ability to process and develop the phonological grammar rules of the universally employed SSP was expected to be hindered or delayed, as a result of exposure to periods of auditory input deprivation and/or relative degradation of the auditory signal. An optimal SSP for CV syllables was present in segments with non-sonorous consonants, to allow for a greater degree of rise from the onset to the nucleus of the syllable. Thus, children with CIs were expected to tap into the perceptual prominence cues in syllables with high sonority (SS syllable), better than syllables with low sonority that lack the perceptual prominence, and rely on SSP (NS syllable).

Furthermore, Kuhl et al. (2008) points out that the infrequent or non-occurring category contrasts in a language could lead to the fading of discriminatory attention for the less-represented contrasts. This could be accompanied by a perceptual narrowing of categories that occurs with experience. For children with CIs, the reduced or degraded audibility of NS contrasts versus SS contrasts could mean that the NS syllable is considered an infrequent representation, with subsequent fading and further sharpening of the SS syllables.

So, the answer to the second question would be that children with CIs perform better in lexical tasks by relying on sonority contour perceptual prominence brought about by highly sonorous lexical segments. This is in line with them being exposed to periods of relative auditory deprivation and degradation of signal input.

**Research Question 3- Do NHC perform differently on sonority-driven perceptual prominence cues versus language dependent cues, and is performance comparable to NHA?**

The NHC were capable of utilizing both the perceptual prominence cues and the language dependent cues of SSP. This is evident through performing equally well on all sonority conditions, even in the condition with the lowest sonority perceptual prominence as in the condition of NS-NS.

Nevertheless, such capability of utilizing SSP-cues is not as well-developed as in adults. This is expressed through the lower accuracy performance of the NHC relative to the NHAs on the NS-NS condition. For NHC, the presence of one syllable with sonority perceptual prominence cue, regardless of position; SS-SS, SS-NS, NS-SS was sufficient to make them score adult-like. This means that NHC continue to rely on sonority perceptual prominence cues to an extent. However, the magnitude of reliance on such prominence cues by NHC is less than that of children with CIs, as evidenced by the adult-like accuracy performance on intermediate conditions. This brings us back to the auditory sensitivity hypothesis (Sussman 1993, 2001) where information processing in young children is affected by salience, loudness or longer duration cues (Ohde & Haley 1997; Sussman 2001).

Gómeza et al. (2014) investigated whether the newborn brains display a predisposition to the SSP by using functional near infrared spectroscopy (Gervain 2011; Lloyd-Fox et al. 2010; Rossi et al. 2012). Results showed that the brain responses of the newborns reacted to syllables like blif, bdif, and lbif in a manner consistent with adults' patterns of preferences, despite having little to no linguistic experience. They concluded that sonority-related bias in humans does not require extensive linguistic experience or ample practice with language production. In the current study, the fact that NHC scored less accurately than the NHA only on the NS-NS condition guide us to think that SSP is a learnable principle rather than being purely innate.

This is particularly important, as such a notion of SSP being learnable, would open the way for auditory rehabilitation tools that aim to abolish the static template-driven word learning and enhance the lexical access performance across different sonority conditions in children with CIs. Such tools would focus on training the auditory input through frequent presentation, as in children the representation of word forms that are frequently heard becomes more robust (Vihman 2016).

The answer to research question 3 is that NHC do not perform differently on sonority-driven perceptual prominence cues versus language dependent cues, as they are able to utilize both. However, they fall behind the NHA on NS-NS condition. A condition that is challengeable in terms of perceptual prominence and requiring the high dependency on SSP. This leads to the assumption that SSP is a learnable principle.

**Research Question 4- Do children with CIs vary in lexical access strategies relative to their normal-hearing peers, being exposed to periods of relative auditory deprivation and relatively degraded auditory signal input?**

Children with CIs appear to adopt an early word-learning strategy termed template-driven (SS-SS) word learning. In typically developing children, the whole-word learning is an early word learning strategy that spurs further vocabulary acquisition within a lexicon. However, this strategy doesn't continue in later stages of development, as the child eventually comes to master more complex adult sequences of articulation, speech planning and memory representation. Moreover, the template shape itself is dynamic rather than being static to a single form (Vihman & Keren-Portnoy 2013). The SS-SS word template, being highly perceptually prominent amidst a period of auditory deprivation makes it fit as an ideal learnable template.

The subgroup analysis attempted to answer the question whether children with CIs when exposed to language for equal periods as normal- hearing children would still adopt the deviant word-learning strategy, or whether they would adopt similar strategies to the NHC. However, it is important to note that even though children are matched on hearing age, the actual oral language exposure of the children with CIs is not essentially equivalent to that of the NHC. This is because the children with CIs are exposed to degraded hearing experience via electric stimulation, as opposed to acoustic hearing available to NHC.

In terms of accuracy performance, results showed that whether children groups are matched according to the oral-language exposure period or chronological age, they still exhibit the same pattern of superior performance on SS-SS condition relative to NS-starting conditions. NHC subgroup continued to show equal performance across all conditions. It thus appears that even with matching of the oral-language exposure period, the children with CIs still employ a deviant strategy compared to the NHC. It is important to note that whether according to the chronological or hearing age, children with CIs had statistically lower receptive vocabulary scores, and greater number of children with non-age-appropriate articulation relative to the NHC. This shows that even with equivalent oral-language exposure period, children with CIs in the current sample had a less developed language relative to the NHC which is in line with the hypothesis of delayed/hindered language learning rule of SSP.

Furthermore, the template-driven word learning strategy appeared to be more evident when children with CIs were matched with NHC in hearing age. This was demonstrated by the consistent high accuracy score of 100% on the SS-SS condition obtained by all children with CIs in the subgroup analysis. Furthermore, children with CIs showed statistically equivalent RT on the SS-SS condition when matched in hearing age but not chronological age. That is, the children with CIs show increased proficiency and less effortfullness on the preferable template SS-SS, when matched in hearing age.

Another interesting finding in the current study was that the lexical access in children with CIs appeared to be partially driven by the initial segment of the word, as demonstrated by the statistically superior performance on SS-SS condition relative to conditions that start with an NS syllable but not SS syllable. Yet, performance is not solely driven by the initial syllable or else a statistically significant difference between SS-NS condition and conditions beginning with NS should have been observed as well. Jusczyk et al. (1999), suggest that paying attention to the beginning of words is a useful strategy for early word learners. It could be that children with CIs are employing the template driven word learning along with a specific onset-emphasis strategy. However this is unlikely as the two strategies occur in different developmental stages in the normal-hearing individuals rather than concomitantly. The current study involved a wide age range of tested children with CIs; 4 ; 11 – 15 ; 2. It is thus possible that some of the children in the sample are adopting a template driven word learning strategy, while others are segmenting the word with emphasis on the initial syllable. Future work studying the effect of sonority conditions across the different age groups could provide a deeper insight.

The current study RT analysis has provided additional evidence that oral-language exposure period is a key factor in developing the auditory processing skills for the children with CIs. Children with CIs showed statistically significantly longer RTs relative to their normal-hearing peers on the sonority auditory task as an overall, and on SS-SS condition. In a previous study by Grieco-Calub et al. (2009), the RT of spoken word recognition in quiet in two-year-old children with CIs was longer than age-matched NHC. Reaction time was assessed using digital recordings of eye movements to target objects. Grieco-Calub et al. (2009) concluded that the auditory experience, or hearing age of young CI users prolongs the time course of spoken word recognition abilities. In our study, this was further supported by the subgroup analysis, which yielded similar RTs when NHC and children with CIs were matched according to the oral-language exposure period/ hearing age.

The answer to research question 4 is that children with CIs vary in lexical access strategies relative to their normal-hearing peers. The current study sample of children with CIs with age range 4 ; 11 – 15 ; 2 adopt a template-driven word learning pattern, an early stage word learning strategy, following the template SS-SS with possible partial/alternative word onset emphasis. The early word-learning strategies were still adopted in lexical access of children with CIs even with matching of the hearing/ oral-language exposure period. Oral-language exposure period is a key factor in developing the auditory processing skills, in terms of effortfullness and RTs.

## Conclusions

An effect of the sonority-related parameters on the degree of lexical perception of children with CIs was demonstrated. Children with CIs perform better in lexical tasks relying on sonority perceptual prominence brought about by the highly sonorous lexical segments within the sonority condition SS-SS. They adopt an early stage word learning strategy known as template-driven word learning. The sonority condition SS-SS in individuals known to have restored audibility and good temporal processing makes it an adequate lexical template choice. In the current study broad age sample, lexical access was partly driven by the initial syllable in children with CIs, another early word learner's strategy, as evident by the superior performance on SS-SS condition relative to NS-initial words only. Template-driven word learning strategy has a predominant role in lexical access of children with CIs even when matched to NHC on the hearing/ oral-language exposure period. NHC demonstrate their ability to shift between and utilize both types of sonority cues, namely perceptual prominence and SSP. The lexical access performance in NHC of the current sample is not template-driven. Compared to the NHA, the NHC rely on perceptual prominence cues but to a lesser extent than children with CIs indicating the developmental nature of perceiving the SSP cue during phonological acquisition. .

## Future Work

Cross linguistic studies -- controlling for token effect a priori -- would validate the outcomes of the current study addressing a language-universal rule. Further probing of the possible underlying causes of the variation in performance of children with CIs relative to normal-hearing individuals will provide a way to inform clinical practice and guide intervention. Studying different age groups of preschoolers and school-aged children will allow defining of the specific strategies employed of template word learning versus initial syllable preference. It may also provide insights to the developmental pattern of SSP. Longitudinal studies that monitor the progress of children with CIs are the ultimate method to observe the developmental effect. This collective knowledge would allow the creation of an evidence-based auditory rehabilitation tool that employs sonority conditions as a pillar on which further new advances could be built. Such optimization of the performance across the different sonority conditions in children with CIs is expected to aid in their lexical access and language development outcomes.

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## Figure Legend

**Figure 1:** Flow chart of the Sonority Experiment Trial

**Figure 2**: Praat waveform, spectrogram and intensity contour of the token /vamo/ with demarcation of the phoneme boundaries and the sound peak minima of consonants.

**Figure 3:** Bar chart comparing the receptive vocabulary score performance across children test groups. Different letters (a, b) indicate significant differences across groups according to one-way ANOVA at $p < 0.05$.

**Figure 4:** Box plot comparing the median accuracy percent correct scores and interquartile ranges of the sonority-treated lexical perception task in the three different experimental groups. Different letters on comparison between groups indicate significant differences according to Mann-Whitney *U* test at $p < 0.05$. Horizontal Line indicates chance level.

**Figure 5:** Cluster Bar chart comparing the sonority accuracy percent correct score on the different sonority conditions within and across test groups. Different letters (a, b) indicate significant differences across groups for each sonority condition according to Mann-Whitney *U* test at $p < 0.05$. Brackets denotes significant differences between sonority conditions within each test group according to Wilcoxon at $p < 0.05$ (*) and $p < 0.01$ (**).

**Figure 6:** Bar chart comparing the visual and sonority-related average reaction time in msec (mean and SD) across the three groups. Different letters across groups indicate significant differences for the visual and the sonority task reaction times separately, according to post hoc tests with Bonferroni correction at $p < 0.05$.

**Figure 7:** Cluster Bar chart comparing the reaction time in msec (mean and SD) on the different sonority conditions across test groups. Different letters within each sonority condition indicate significant differences between experimental groups according to post hoc test with Bonferroni correction at $p < 0.05$.

**Figure 8:** Box plot comparing the median accuracy percent correct scores and interquartile ranges of the sonority-treated lexical perception task in the children subgroups matched according to oral-language exposure period. There are no statistically significant differences according to Mann-Whitney *U* test at $p < 0.05$ between subgroups. Horizontal Line indicates chance level.

**Figure 9:** Cluster Bar chart comparing the sonority accuracy percent correct score performance on the different sonority conditions across and within children subgroups matched according to oral-language exposure period. Different letters (a, b) indicate statistically significant differences between sonority conditions within each children subgroup according to Wilcoxon at $p < 0.05$. There are no statistically significant differences across groups for each sonority condition according to Mann -Whitney *U* test at $p < 0.05$

**Figure 10:** Bar chart comparing the visual and sonority-related average reaction time in msec (mean and SD) across the children subgroups matched according to oral-language exposure period age. There are no statistically significant differences on visual and sonority task reaction times separately according to independent-samples *t* tests at $p < 0.05$.

**Figure 11:** Cluster Bar chart comparing the reaction time in msec (mean and SD) on the different sonority conditions across the children subgroups matched according to oral-language

exposure period. There are no statistically significant differences across the subgroups according to independent-samples *t* tests at $p < 0.05$

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# Sonority's Effect as a Surface Cue on Lexical Speech Perception of Children with Cochlear Implants

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## ABSTRACT

**Objectives** Sonority is the relative perceptual prominence/loudness of speech sounds of the same length, stress, and pitch. Children with cochlear implants (CIs), with restored audibility and relatively intact temporal processing, are expected to benefit from the perceptual prominence cues of highly sonorous sounds. Sonority also influences lexical access through the sonority sequencing principle (SSP), a grammatical phonotactic rule, which facilitates the recognition and segmentation of syllables within speech. The more non-sonorous the onset of a syllable is, the larger is the degree of sonority rise to the nucleus, and the more optimal the SSP. Children with CIs may experience hindered or delayed development of the language learning rule SSP, as a result of their deprived/degraded auditory experience. The purpose of the study was to explore sonority's role in speech perception and lexical access of prelingually deafened children with CIs.

**Design** A case-control study with 15 children with CIs, 25 normal-hearing children and 50 normal-hearing adults was conducted, using a lexical identification task of novel, non-real CV-CV words taught via fast mapping. The CV-CV words were constructed according to four sonority conditions, entailing syllables with sonorous onsets/ less optimal SSP (SS) and non-sonorous onsets/ optimal SSP (NS) in all combinations, i.e. SS-SS, SS-NS, NS-SS and NS-NS. Outcome measures were accuracy and reaction times. A subgroup analysis of 12 children with CIs pair-matched to 12 normal-hearing children on hearing age aimed to study the effect of oral-language exposure period on the sonority-related performance.

**Results** The children groups showed similar accuracy performance, overall and across all the sonority conditions. However, within group comparisons showed that the children with CIs

scored more accurately on the SS-SS condition relative to the NS-NS and NS-SS conditions, while the normal-hearing children performed equally well across all conditions. Additionally, adult-comparable accuracy performance was achieved by the children with CIs only on the SS-SS condition, as opposed to NS-SS, SS-NS and SS-SS conditions for normal-hearing children. Accuracy analysis of the subgroups of children matched in hearing age showed similar results. Overall longer reaction times were recorded by the children with CIs on the sonority-treated lexical task, specifically on the SS-SS condition compared to age-matched controls. However, the subgroup analysis showed that both groups of children did not differ on reaction times.

**Conclusions** Children with CIs performed better in lexical tasks relying on the sonority perceptual prominence cues, as in SS-SS condition, than on SSP-initial relying conditions as NS-NS and NS-SS. Template–driven word learning, an early word learning strategy, appears to play a role in the lexical access of children with CIs whether matched in hearing age or not. The SS-SS condition acts as a preferred word template. The longer reaction times brought about by the highly accurate SS-SS condition in children with CIs is possibly because listening becomes more effortful. The lack of reaction times difference between the children groups when matched on hearing age points out the importance of oral-language exposure period as a key factor in developing the auditory processing skills.

# INTRODUCTION

## Cochlear Implants and Speech Perception

Cochlear implantation has been gaining growing acceptance as an effective treatment for individuals with severe-to-profound sensorineural hearing loss. As a result, the number of pediatric cochlear implants (CIs) has been distinctly growing (Bradham & Jones 2008). According to the US National Institute of Health (2012), there are approximately 324,200 individuals with CIs worldwide. The benefits of CIs during the course of language acquisition have been documented for both speech perception and speech production (Fu & Galvin 2007; Shannon 2012).

Speech acoustic cues, including temporal-spectral ones, comprise the segmental (phonetic) features of the individual phonemes (Snow 2001). Individuals with CIs can demonstrate good word recognition accuracy; however it is unclear how they utilize the various acoustic cues to contribute to phonetic perception (Winn et al. 2011). Research efforts should be expanded to better recognize, identify and understand the way these cues are utilized in language processing, as this knowledge could guide the development and tailoring of better speech processing algorithms and rehabilitative tool outcomes (Jung et al. 2012; Sagi et al. 2009).

## Sonority and Sonority Sequencing Principle

Sonority (or vowel-likeness) is one of the phonetic/ phonological cues that facilitates the recognition and segmentation of syllables within speech (Ettlinger et al. 2012; Miozzo & Buchwald 2013), thereby aiding child language acquisition (Ohala & Kawasaki-Fukumori 1997; Pater 2009). Sonority by definition, is a scalar property of the relative loudness/ perceptual prominence of a particular sound segment compared to other sounds of the same length, stress, and pitch (Ladefoged 1993; Parker 2008). Sonority has been correlated to the openness of the vocal tract (Goldsmith 1990), with an underlying abstract language-specific phonetic representation (Beckman et al. 1992). Sonorous sounds include vowels, glides, liquids (flaps, laterals), and nasals, while non-sonorous sounds include obstruents (fricatives, affricates, and plosives) (Selkirk 1984). Sonority, being a perceptual aspect, is very difficult to quantify. Various scales have been proposed to order speech sounds on a sonority hierarchy. However, no universal sonority hierarchy exists, specifically when it comes to the ordering of obstruents (Parker 2008; Selkirk 1984; Steriade 1982), with claims of language-specific differences (Steriade 1982). According to Parker (2008) there are at least 98 different correlates of sonority, however very few attempts were made to instrumentally confirm them. Parker (2008) provided physical evidence supporting the sonority hierarchy. A partially new conceptualization of the physical realization of sonority was proposed, namely the sound level values at protrusions or extremes. These are values at the point of maximal and minimal intensity of vowels and consonants, respectively. Phonemes in English, Spanish, and Quechua were analyzed and the sonority intensity values were found to be strongly correlated ($r = 0.91$) with the typical phonological sonority hierarchy indices proposed. The study by Parker (2008) provided an empirical evidence that sonority is correlated with a measurable physical parameter.

The ability of speech sounds to follow one another in phonological strings of a language is defined by the phonotactic rules (Blevins 1995; Chomsky 1969; Jakobson 1968). Sonority plays a grammatical role in defining syllable structure through the language-universal phonotactic principle termed sonority sequencing principle (SSP) (Clements 1990; Selkirk 1984; Zec 1995). According to 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. This sonority-based principle thus determines the position of phonemes within the syllable, where sonority increases maximally and steadily from the onset to the vowel (Clements 1990). Therefore according to SSP, the more optimal the sonority sequencing is, the larger is the degree of sonority rise from the onset to the nucleus of the syllable.

The language-specific knowledge of phoneme co-occurrences affects word segmentation (McQueen 1998; Norris et al. 1997) and syllabification (Redford & Randall 2005; Smith & Pitt 1999; Treiman & Zukowski 1990). Sonority is one of the factors predicting the sequence ordering mastered by young children (Ohala & Kawasaki-Fukumori 1997; Pater 2009), and the rate and type of errors observed in individuals with developmental or acquired language impairments (Bastiaanse et al. 1994; Béland et al. 1990; Buckingham 1986; Christman 1994; Romani & Calabrese 1998; Romani & Galluzzi 2005; Romani et al. 2002; Stenneken et al. 2005). Studies have supported the role of SSP in adult speech perception (Berent et al. 2008; Berent et al. 2007), continuous speech segmentation (Ettlinger et al. 2012), and child language acquisition (Ohala & Kawasaki-Fukumori 1997; Pater 2009)

Several studies have tested the sonority related-grammatical markedness through assessing production and perception of SSP-violating onset clusters versus SSP-adhering ones in typically developing children including Greek, Dutch, English, Hebrew, and Norwegian language (Berent et al. 2011; Clements 1990; Ohala 1999; Syrika et al. 2011; Yavaş et al. 2008). It is widely debated whether the sonority related-grammatical markedness is innate or learned (Parker 2008). Infants as young as nine months of age have been shown to favor SSP- adhering syllables like “blif” over SSP-violating syllables like “lbif”, despite no experience with either (Friederici & Wessels 1993). However, the cumulative knowledge about SSP-adhering and violating structures in a language is suggested to be learnable, as demonstrated by the fact that each language has different phonotactics (Redford 2008) and also by experiments that tested the ability to learn novel phonotactic patterns over a set of data (Chambers et al. 2003; Dell et al. 2000; Onishi et al. 2002; Warker & Dell 2006).

Sonority, as one of the factors influencing word segmentation and the sequence ordering mastered by young children, is thus expected to play a role in the process of lexical access and acquisition, which is mediated by a fast-mapping strategy between the referent and lexical label.

## Lexical Access

A mental representation of a word must exist for the individual to be able to recognize it. In adults, acoustic spectra, among other cues of semantics, syntax and category, represent and provide access to the word in a speaker's lexicon. Lexical access in adults is facilitated by the representation of a word as a unique combination of small number of units (syllable, foot, mora) (Bertoncini & Mehler 1981). What children attend to in the process of lexical acquisition is not fully clear. Suggestions exist that during the first 6-12 months of life, infants utilize acoustic-phonetic mechanisms to store only stressed and word-initial syllables, as they find a way into the language system (Echols & Newport 1992; Gleitman & Wanner 1982). Later on, when the child has reached the understanding that words are used to name categories of objects and events, it adopts a holistic, less analytic approach in which semantic content rather than fine phonetic discrimination is of primary importance (Charles-Luce & Luce 1990; Ferguson & Farwell 1975; Hallé & de Boysson-Bardies 1994; Merriman & Schuster 1991). This whole-word processing starts around the period they have acquired 30 productive words and may last several years, as basic knowledge of words and related conceptual distinctions build up. Template-driven word learning is a form of whole-word processing, with a tendency for learning words with a particular prosodic frame. The word-template acts as a lexical generalization that later spurs further learning of words that fit into the same template (Macken 1979).

### Fast Mapping

Fast mapping is the capability of learning a word after minimal exposure to the new label. It develops during the period of whole-word learning (Jaswal & Markman 2001) and involves two essential processes; referent selection and referent retention. Referent selection is the process by which the child determines the correct referent of a novel label. Referent retention is the process of storage of this newly formed label–object mapping in the memory for later use. During natural conversation, children are exposed to novel words frequently, and therefore should be able to perform these tasks rapidly and repeatedly (Spiegel & Halberda 2011).

### Sonority Research in Individuals with CIs

Very few studies have investigated the role of sonority in speech of children with CIs. Chin and Finnegan (2002) examined variations in English complex onset realizations by children who use CIs. Results showed that one-segment realizations generally respected sonority principles, with the more sonorous segment being omitted and the less sonorous one retained. Kim and Chin (2008) investigated fortition and lenition patterns of error production in children with CIs. Fortition strengthens consonant articulation, that is, it makes the consonants less sonorous, while lenition weakens consonant articulation, thereby it makes the consonants more sonorous (Brandão de Carvalho et al. 2008). Data supported that lenition errors reflect the minimization of articulatory effort in specific phonological contexts, while fortition errors are pervasive and not context-sensitive in the same way that lenition errors are. The resulting pattern was consistent with early phonological stage patterns of normal-hearing children, and suggested that phonological development in the two groups reflects a single universal acquisition pattern based on markedness. However, both studies investigated the role of sonority on speech production, rather than on speech perception and lexical access.

## Study Rationale, Hypothesis, and Objectives

For CI users, temporal processing can be as good as that of normal-hearing listeners, as evidenced by temporal modulation transfer functions (Shannon 1992) and gap detection tasks (Shannon 1989). Thus, children with CIs are expected to detect the perceptual prominence cues provided by the sonority contour of highly sonorous consonants, equivalent to their age-matched normal-hearing children (NHC). Sonority also influences lexical processing through the phonological grammar rule of SSP. Sonority sequencing principle, being a language learning rule, is expected to be delayed or hindered in children with CIs as a result of the earlier period of auditory deprivation and the relatively degraded auditory signal provided by CIs. Furthermore, children with CIs may shift to rely on the more accessible cue of sonority perceptual prominence as a compensatory strategy. Therefore, we hypothesize that children with CIs and normal-hearing peers differ in terms of lexical access performance.

The goal of the current study was to explore the role of sonority in terms of the perceptual prominence cues versus SSP cues in the lexical access of prelingually deafened children with CIs. The current research addressed the following questions: 1- How do the sonority related parameters affect the degree of lexical perception in children with CIs, relative to normal-hearing NHC and normal-hearing adults (NHA)? 2- Do children with CIs perform better in lexical tasks by relying on perceptual prominence cues brought about by highly sonorous lexical segments or do they rely on language learning rules evidenced by sonority sequencing cues? 3- Do NHC perform differently on sonority-driven perceptual prominence cues versus language dependent cues, and is their performance comparable to NHA? 4- Do children with CIs vary in lexical access strategies relative to their normal-hearing peers, being exposed to periods of relative auditory deprivation and relatively degraded auditory signal input?

# METHODS

## Participants

A Case-Control study was conducted including three groups of Greek-speaking participants; 15 children with CIs, 25 NHC and 50 NHA. The sample size of children with CIs was guided by the availability of children complying with the inclusion criteria. Larger sample sizes were included for the normal-hearing groups, as they are of easier access, to provide reference data for performance in NHA and NHC. Power analysis was not possible as the predicted outcome value was unknown.

Children with CIs included in the current study were prelingually deaf, as defined by an age of implantation of maximally 3 years. A postimplant age of at least two years was set to ensure that participants had some experience with spoken language and were able to perform the task under test using the fast mapping procedure. Additionally they had to be monolingual, with normal nonverbal Intelligence Quotient (NVIQ), and no additional disabilities. Proper audibility/functionality of the CI device with recent mapping within the last six months was also set within the inclusion criteria. All of the children with CIs were unilateral users. The age and postimplant age of each of the children with CIs are depicted in Table 1. The NHC were matched to the children with CIs based on the chronological age range, and gender. Inclusion criteria for the typically developing (TD) NHC included normal hearing, normal NVIQ, and age-appropriate speech and language skills. The NHA were matched on the basis of gender to the two groups of children. Inclusion criteria for NHA included normal hearing, with age limit set at 40 years to avoid potential memory influences on the fast mapping referent retention process. Inclusion criteria was employed by the referring audiologist, and further validated through a set of pretest interview questions administered by the first author to the attending parent.

Informed Consents were obtained from all the participants above 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 AHEPA hospital/Thessaloniki and by the Special Committee of Research Ethics of UOM/Thessaloniki.

## Materials

A battery of tests was selected including the sonority experiment, audiological, speech and language tests, as described in the next section. Audiological tests included oto-acoustic emissions and pure tone audiometry to ensure normal hearing of the control groups. Moreover, for children with CIs, in free field, pure tone average (PTA) thresholds were at least 25 dB HL to ensure proper functionality of the CI device. In addition, speech audiometry tests were done to document the speech recognition abilities of the children with CIs. Aided free-field pure-tone average thresholds (500 Hz-2 kHz), and speech audiometry correct percent scores (word and sentence) of the children with CIs are depicted in Table 1. Raven IQ test (Raven et al. 2000, updated 2004) was employed to ensure normal NVIQ using the available Greek norms for the children aged up to 11 ; 11. Three NHC and two children with CIs, outside the current sample of 25 NHC and 15 children with CIs, who scored at or below the $10^{th}$ percentile (Grade of IV- and

V), were excluded. For older children, attendance of mainstream schools with at least medium academic achievement was used as an indicator of normal NVIQ. A protocol of receptive vocabulary in Greek was used to compare the receptive language scores of both children groups, and to ensure that the NHC were TD using the Greek norms up to the age of 6 ; 11. Attendance of mainstream schools with at least medium academic achievement was used as an indicator of TD language in NHC with age 7; and higher. The Test of Articulatory and Phonological Development (PAL 1995) was used to compare qualitatively the phonological skills of both children groups, and to ensure that the NHC are TD. The battery of test took 50 minutes on average depending on the child's age and responsiveness.

In addition, a novel fast mapping experiment was designed to test the hypothesis of the sonority-related lexical perception.

## Sonority Experiment

### Sonority-Related Experiment Design

The Sonority Experiment was a computer-based, lexical identification task of newly-learned CV-CV words. The CV-CV words were labels of funny objects learned via fast mapping procedures. E-Prime 2.0 Professional software (Psychology Software Tools Inc 2012) was used to build the experiment. Audio stimuli included 16 disyllabic, novel, non-real CV-CV words with a trochaic prosodic structure within four sonority conditions. Funny objects were selected as pictures, obtained with author’s permission from a previous study by MacRoy-Higgins et al. (2013).

## Sonority-Related Experiment Procedure

Figure 1 illustrates the procedure for one trial, which is repeated for all of the 16 trials of the experiment. Each trial consisted of a pair of CV-CV words of opposing sonority conditions, as explained in the following section. The fast mapping (Spiegel & Halberda 2011) procedure was used to familiarize the funny 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 millisecond (msec), to ensure that identification was based on presentation of discrete trials. The insertion of a foil within the identification slide was guided by the pilot study (Hamza et al. 2016) where the two picture array's chance level was relatively high (79.16% at $p < 0.05$), while that of the three picture array format was 52.75% at ($p < 0.05$). Both accuracy measures and reaction times (RTs) (from the offset of the target-word audio) were recorded and logged through the touch screen.

## Sonority-Related Experiment Test Setting

Testing took place at AHEPA Audiology Clinic sound treated room. A story scenario was developed to instruct the children. A practice session including six trials (two with real object words and four with novel words) was employed before testing. A pass score criteria of 50% in the trial session was mandatory before moving on to the testing. Hand position was standardized using a palm-shaped pad, with versions customized for left- and right-handed participants. Audios were played through two loudspeakers placed at 45 degree Azimuth calibrated at 70 dB HL at 70 cm from seating position. Testing session lasted 20 minutes including the practice.

## Sonority-Related Experiment Stimuli

According to the sonority hierarchy, vowels (V) within the CV-CV novel words are always sonorous (S), consonants (C) could be sonorous (S) or non-sonorous (N). The test stimuli building blocks of words were thus sonorous syllables (SS) and non-sonorous syllables (NS). The SS syllable is perceptually-prominent as it is composed of two sonorous phonemes, and has a less optimal SSP as it has a relatively smaller degree of sonority rise from the onset to the peak of nucleus. The NS syllable exhibits the opposite profile where it has a more optimal SSP as a result of the larger degree of sonority rise from onset to peak, and a less perceptually-prominent sonority contour caused by the non-sonorous consonant. This yields four possible sonority testing conditions at a lexical level; NS-NS, NS-SS, SS-NS, and SS-SS. At a word level there are three hierarchies within the sonority conditions. The NS-NS condition has low sonority perceptual prominence and an optimal SSP, NS-SS and SS-NS have medium sonority contour perceptual prominence and mid-optimal SSP profile, while SS-SS has a high sonority contour perceptual prominence and a least optimal SSP profile. The mid-hierarchy classes allow for studying the interaction of sonority with syllable position: first vs second. Four different tokens, containing different consonants and vowels, were generated per sonority condition, yielding the 16 different novel word stimuli (4 conditions x 4 tokens). Sonorous onset consonants included flaps, laterals, and nasals. The Greek language lacks glides (Mennen & Okalidou 2007). Non-sonorous onset consonants included voiced and voiceless fricatives, voiced and voiceless stops (Parker 2008; Selkirk 1984). The current study did not include affricates, as many sonority scales ignore this class entirely, because of their inherent complications to classify as a single phoneme or cluster (Escure 1977; Hankamer & Aissen 1974; Lavoie 2001). Refer to Table 2 for an inventory of the sonority experiment stimuli, the sonority condition and phonemic content.

Phonotactic probability, the likelihood of occurrence of a sound sequence, facilitates spoken word recognition and production. The more common sound sequences are, the more accurately and/or faster they are recognized (Storkel & Lee 2011). In the current study, the frequency of occurrence of the CV syllables of the word stimuli was controlled for by matching them to a medium frequency of occurrence in the Greek language, with respect to syllable position. The frequencies of occurrence of syllables in Greek were calculated from a database (Adamidou et al. 2013) of the 20000 most frequent lemmas in Greek (consult Supplemental Digital Content 1.doc for the detailed procedure of calculation and matching). Novel words did not contain phonemes with the same place of articulation and manner to avoid confounding effects in perception due to syllabic similarity. The sonorous phonemic classes: flaps, laterals, and nasals were represented unevenly in the first vs. second position, due to the fact that there are only three classes versus 8 presentations of the sonorous class in each position. The choice of phoneme class representation in different positions was guided by an effort to counterbalance language bias frequency effects towards syllable position in the Greek language. The CV-CV stimuli were then paired into eight pairs of opposing sonority conditions, with creation of all possible pairing combinations.

Each novel word was randomly assigned to the picture of a funny object within the 8 pairs. Each of the 8 pairs was presented twice with alterations of the target word through a random process. Four different versions of the novel word- picture assignment, trial order, target word order and picture position were created. Choice of the test version administered to the participant was through systematic random assignment.

## Acoustical Analyses of the Stimuli for the Sonority Experiment

Novel word stimuli as well as carrier phrases were recorded by a native Greek female speaker using Sony PCMD100 Portable High Resolution Audio Recorder in a sound treated booth. The carrier phrase and the target word were collated via Sony Sound Forge Pro10.0. Then the collated phrases were normalized to a peak level of 80 dB HL on Gold wave (GoldWaveInc 2015) to ensure that the results under test were not due to differences in presentation intensity. The mean intensity output was measured for each sonority condition using PRAAT (Boersma & Weenink 2016). For NS-NS the mean intensity +/- SD was 70.5 dB +/- 3.1 dB, for NS-SS was 71 dB +/- 1.6 dB, for SS-NS was 69.4 dB+/- 1.7 dB, and for SS-SS was 70.6 dB +/- 1.1 dB.

Acoustic analyses of the stimuli were conducted using Parker (2008) methodology to provide a physical correlate of the sonority classes of non-sonorous vs. sonorous consonant components. For this the sound minima peak intensity value was determined for the various consonants in the sonority classes with respect to syllable position (consult Supplemental Digital Content 2.doc for the detailed procedure of measurement). Figure 2 illustrates the token “vamo” as an example for the measurements performed on PRAAT. Table 3 illustrates the intensity minima values recorded for the various phonemes in the CV-CV word stimuli. An independent-samples *t* test showed that the dB minimum value of the sonorous consonants were statistically higher than the non-sonorous consonants in the first position [$t(8.024) = 4.516$, $p=0.002$] and the second position [$t(9.053) = 7.344$, $p<0.001$]. Furthermore, four real Greek words that were recorded by the same speaker and used in the training phase were analyzed using the same Parker (2008) methodology on PRAAT. Table 4 shows that similar sonority measurement patterns were observed for the Greek real words as for the novel word stimuli.

### Visual Reaction Time Experiment

A nonverbal, visual task was added, as a control condition, to ensure that the process of picture selection had no influence on the RT results. Absence of RT differences between groups on the visual task excludes generic motor differences in the process of picture selection between the two groups. This will allow for conclusions to be drawn upon the actual impact of the auditory component of the sonority experiment.

The Visual localization experiment was run after the sonority experiment within the same session. The task involved a rabbit appearing on the screen in one of the three picture positions and the child was instructed to catch the rabbit as quickly as possible by touching the screen in the same manner as in the sonority experiment. Then the child would return his hand to the palm shaped pad and when ready, the procedure was repeated again for a total of eight trials. The RT was measured from the onset of appearance of the rabbit on the screen until the touch of it. The quickest visual RT of all eight trials was taken as the outcome measure.

### Data Analyses

The two major outcome performance measures of the sonority experiment were accuracy and RTs. Accuracy was expressed in percent correct score and RT was expressed in msec. The upper weight in performance judgment was given to accuracy, 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 first author, were removed from the data set. The percent of trials eliminated from the RT data set was 3.25% for NHA, 9.5% for NHC, and 15.8% for children with CIs. An alpha level of 0.05 was used for all statistical tests.

The accuracy percentage scores in the sonority-treated lexical perception task were not normally distributed even after log 10 transformation. Therefore, non-parametric 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 if pairwise comparisons were required. For within group comparisons the Friedman one way ANOVAs was applied, followed by Wilcoxon test if pairwise comparisons were required.

The visual task RT was normally distributed and so between group comparisons were performed using one-way ANOVA, with post hoc tests using the Bonferroni correction for multiple comparisons. The sonority experiment RT data were log10 transformed in order to achieve normality and, homoscedasticity of model's residuals before being analyzed via Mixed Linear Models using the ANOVA method. Due to the hierarchical nature of the data, the model involved a "between subject factor" (factor "Group", with three levels: NHA, NHC, and CI) and two "within subjects factors" with repeated measures (factor "Sonority Condition", with 4 levels: [NS-NS, NS-SS, SS-NS, SS-SS], and factor "Token.RT" with four levels nested within the levels of Sonority Condition). In the proposed model the subjects were considered a random effect factor nested within the three groups. Pairwise comparisons of mean values were performed by means of posthoc tests using the Bonferroni correction for multiple comparisons. For conceptual reasons, RT data are reported at the untransformed raw values.

A subgroup analysis was performed based on 12 children with CIs which were pair matched with 12 NHC according to the hearing/ oral-language exposure period. The oral-language exposure period was defined as the postimplant age in the children with CIs and the chronological age for the NHC. This analysis was carried out to study the effect of the oral-language exposure period on the performance of children with CIs, relative to NHC on the sonority task. As for the full sample analysis, the accuracy percentage scores were not normally distributed even after log 10 transformation. Therefore, non-parametric tests were applied to the raw untransformed data. For between group comparison Kruskal Wallis test was used for main effects, followed by Mann-Whitney *U* test if pairwise comparisons were required. For within group comparisons Friedman one way ANOVAs were used, followed by Wilcoxon test if pairwise comparisons were required. Both the visual RT and sonority RT data were normally distributed. An independent-samples *t* test analysis was used for between group comparisons.

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

## RESULTS

### Demographics

The mean age of the two children groups was not found to be statistically different, as shown by an independent-samples *t* test [t (38) = 0.494, p = 0.624]. Chi-square test of independence showed that all the studied groups had statistically similar distributions for gender (chi-square test of independence, $X^2 = 0.142$, df = 1, p = 0.931). Table 5 shows the age and gender distribution of the different groups. An independent-samples *t* test comparison of the Raven NVIQ test scores of the two children groups showed statistically similar performance [t (37) = 0.488, p = 0.628]. However, on the receptive vocabulary test, statistically significantly higher scores were obtained by the NHC relative to the children with CIs using an independent-samples *t* test [t (37) = 5.267, p < 0.01], as shown in Figure 3. Chi-square test of independence showed that the group of children with CIs entailed a statistically significantly higher number of children with non-age appropriate articulation relative to the NHC (chi-square test of independence, $X^2 = 16.501$, df = 1, $p < 0.01$).

All NHC were TD as validated through the normal hearing thresholds at all frequencies, normal NVIQ through Raven NVIQ scores or School report, normal receptive vocabulary scores or School report, and age appropriate phonological development on Articulation test assessed by Speech-Language Pathologist.

**Overall Accuracy Performance on Sonority-treated Lexical perception Task**

The accuracy performance on the sonority-treated lexical perception task ranged between 93.75% - 100% for the NHA group, 68.75% - 100% for the NHC group and 62.5% - 100% for the children with CIs group. Median accuracy percentage performance was 100% for both normal-hearing groups, whereas it was 93.75% for children with a CI. Kruskal Wallis analysis showed a statistically significant main effect of 'groups' on the overall accuracy performance ($p < 0.001$). Pairwise comparison using Mann-Whitney *U* test showed that the NHA scored statistically significantly more accurately than both the NHC ($U = 409$, df = 74, $p = 0.002$)] and children with CIs ($U = 150$, df = 59, $p < 0.001$)]. Yet, both groups of children did not score statistically different ($U = 140.5$, df = 39, $p = 0.167$), as illustrated in Figure 4. The more accurate performance of adults relative to the children groups, but not between age-matched children groups reflects underlying age-related developmental cognitive and language acquisition processes. A positive correlation between the sonority experiment lexical identification accuracy score and the receptive vocabulary score for the entire children sample, was shown $r = 0.53$, $p < 0.001$. That is, the higher the receptive score the better the performance on the lexical identification task, or vice versa.

**Group Accuracy Performance on Different Sonority Conditions**

Within group comparisons using Friedman one way ANOVAs showed that there was no main effect of the sonority condition on accuracy performance for the normal-hearing groups whether adults ($\chi2(49) = 1.714$, $p = 0.634$) or children ($\chi2(24) = 3.102$, $p = 0.376$). However, for the children with CIs a main effect of the sonority condition on accuracy performance was detected ($\chi2(14) = 8.711$, $p = 0.033$). Further Pairwise comparison using Wilcoxon test showed that the children with CIs scored statistically significantly higher on the SS-SS condition, a condition relying on perceptual prominence, relative to conditions starting with a non-sonorous (NS) syllable, namely NS-NS ($Z = -2.111$, $p = 0.035$) and NS-SS ($Z = -2.714$, $p = 0.007$). All children with CIs scored 100% correct on the SS-SS condition apart from subject 3, a 5 year old child, with a postimplant age of 3; 1 who scored 75%.

Across group comparisons, Kruskal Wallis analyses showed a main effect of the different experimental groups on the accuracy performance for NS-NS ($p = 0.002$), NS-SS ($p < 0.001$), and SS-NS ($p = 0.027$) conditions, but not for the SS-SS condition ($p = 0.179$). Pairwise comparison using Mann-Whitney *U* test showed that for NS-NS condition the NHA scored statistically significantly more accurately than both groups of children [NHC ($U = 496$, $df = 74$, $p = 0.018$, CI ($U = 228$, $df = 59$, $p < 0.001$)], while both groups of children scored statistically similar ($U=156$, $df=39$, $p=0.294$). For NS-SS and SS-NS conditions, the NHA scored statistically more accurately than the children with CIs [NS-SS ($U = 201$, $df = 64$, $p < 0.001$), SS-NS ($U = 287$, $df = 64$, $p = 0.006$)], and statistically similar to the NHC [NS-SS ($U = 523$, $df = 74$, $p = 0.052$), SS-NS ($U = 574$, $df = 74$, $p = 0.185$)]. Both children groups scored statistically similar on the medium sonority conditions [NS-SS ($U = 130.5$, $df = 39$, $p = 0.112$), SS-NS ($U = 157$, df

= 39, $p = 0.406$)]. Group performance within and across the different sonority conditions are shown in Figure 5.

**Group Reaction Time Performance**

Analysis of the RTs on the rabbit-visual task experiment using one-way ANOVA showed a statistically significant main effect of the test groups on the RT [$F(2, 87) = 7.614$, $p = 0.001$]. Post hoc tests with Bonferroni correction for multiple comparisons revealed that the adult group had statistically significantly faster RTs for the visual task (M = 517 msec, SD = 73 msec) relative to both groups of children [NHC (M = 589 msec, SD = 103 msec, $p = 0.002$); CIs (M = 583 msec, SD = 87 msec, $p = 0.029$)]. However, more importantly, the visual task's RTs of the children groups did not differ statistically from each other ($p=1.000$). This is important, as potential RT differences on the sonority audio-visual task between the children groups could be attributed to the auditory component rather than to the generic psychomotor ability to respond to the visual component. Group performances on the visual task are depicted in Figure 6.

With regard to the average RT on the sonority-treated lexical perception task, the analysis via Mixed Linear Models indicated a statistically significant main effect of Group on the average RT [$F(2, 89) = 23.397$, $p < 0.001$, $\eta 2 = 0.345$]. Post hoc analysis with Bonferroni correction for multiple comparisons showed that the normally-hearing adults (M = 500 msec, SD = 292 msec) yielded statistically significantly faster RTs than both groups of children [NHC (M = 902 msec, SD = 712 msec, $p < 0.001$), CIs (M = 1065 msec, SD = 838 msec, $p < 0.001$)]. This pattern on the audio-visual sonority task is similar to the visual-only task, suggesting that differences in the overall sonority RT between adults and children result at least partially from generic motor effects. The RT on the sonority-treated lexical perception task of the children with normal-hearing was statistically significantly faster than that of the group of children with CIs ($p <$

0.001). As indicated previously, there were no RT differences between the children groups on the rabbit-visual task. Thus the RT differences between the children groups on the sonority-treated lexical perception task are attributed to the processing load brought by the auditory/verbal component. In other words, the normally-hearing children processed the auditory/verbal stimuli faster than children with CIs.

Within the methodological frame of Mixed Linear Models there was no main effect of sonority on the RT [F (3, 346) = 2.13, $p = 0.096$, $\eta 2 = 0.018$]. Additionally, there was no interaction between group and sonority condition [F (6, 328) = 1.2, $p = 0.306$, $\eta 2 = 0.022$]. However, due to the statistically significant main effect of Group on the average RT, further exploration was carried out to define any specific sonority conditions by which the groups varied in their Sonority RT. Post hoc tests with Bonferroni corrections showed that the NHA [NSNS (M = 500 msec, SD = 31 msec), NS-SS (M = 527 msec, SD = 32 msec), SS-NS, (M = 495 msec, SD = 32 msec), SS-SS (M = 480 msec, SD = 31 msec)] were statistically significantly faster on all conditions than both groups of children [NHC: (NSNS: M = 897 msec, SD = 48 msec, $p < 0.001$), (NS-SS: M = 933 msec, SD = 47 msec, $p < 0.001$), (SS-NS: M = 1095 msec, SD = 47 msec, $p < 0.001$), (SS-SS: M = 821 msec, SD = 48 msec, $p < 0.001$); CIs (NSNS: M = 1163 msec, SD = 67 msec, $p < 0.001$), (NS-SS: M = 1028 msec, SD = 69 msec, $p < 0.001$), (SS-NS: M = 1076 msec, SD = 70 msec, $p < 0.001$), (SS-SS: M = 1114 msec, SD = 60 msec, $p < 0.001$)]. Comparison between the children groups showed that NHC had statistically similar RTs as the children with CIs on all sonority conditions [NSNS ($p = 0.087$), NS-SS ($p = 0.382$), SS-NS ($p = 0.216$)] except for the condition SS-SS ($p = 0.015$), where the children with the CIs were statistically significantly slower than the NHC. Even though children with CIs showed equivalent accuracy on SS-SS condition to not only the NHC but also to the adults, a statistically longer RT was needed by them, in order to achieve such high levels of accuracy on SS-SS condition. Reaction time on the different sonority conditions, across the experimental groups is shown in Figure 7.

**Token Analysis**

Token analysis was carried out to ensure that the hypothesis under test was not driven about by the effect of a specific token within a sonority condition. For each of the test group's sonority conditions, the four tokens within yielded statistically similar accuracy scores according to Mcnemar test with Bonferroni corrections for multiple comparisons. Across groups comparison of individual token accuracy scores using Chi-square test of independence showed no statistically significant differences between the three groups for any of the 16 tokens, after Bonferroni corrections for multiple comparisons. This rules out that the sonority condition's accuracy results were driven by a single token effect.

Analysis of the token's RT within the methodological frame of Mixed Linear Models using the ANOVA method showed a statistically significant interaction of tokens nested within the sonority conditions and the test groups (Condition x Token x Group) ($F = 1.784$, $df = 24$, $p = 0.012$). Post hoc tests with Bonferroni corrections for multiple comparisons showed that the token "mola" was the sole token within the SS-SS sonority condition with statistically significantly longer RTs for the children with CIs ($M = 1375$ msec, $SD = 1138$ msec) relative to the NHC ($M = 772$ msec, $SD = 560$ msec). This means that the RT of the SS-SS condition could have been driven by this single token. However, it is worth mentioning that, two of the remaining three tokens within the SS-SS condition were also of longer RT in the children with CIs relative to the NHC, yet not statistically significant.

**Subgroup Analysis**

Twelve children with CIs were pair matched with 12 NHC according to the oral-language exposure period. This analysis was carried out to study the effect of the oral-language exposure period on the performance of children with CIs on the different sonority conditions, and further probe the possible causes for the difference in the performance between the two groups of children.

The oral-language exposure period ranged from 3 ; 2 – 12 ; 8 (M = 7 ; 10 years, SD = 3;2 years) for children with CIs and 3 ; 8 – 13 ; 6 (M = 7 ; 9 years, SD = 3 ; 1 years) for NHC. The chronological age ranged from 6 ; 1 – 15 ; 2 (M = 10 ; 10 years, SD = 3 ; 3 years) for children with CIs and 3 ; 9 – 13 ; 6 (M= 7;11 years, SD = 3;3 years) for NHC. An independent-samples *t* test showed that the subgroups did not differ statistically according to the chronological age [t (22) = 1.701, p = 0.103]. An independent-samples *t* test comparison of the receptive vocabulary test scores continued to show a statistically significantly [t (21) = 2.814, p = 0.01] higher performance for the NHC (M = 103 score points, SD = 35 score points) relative to the children with CIs (M = 69 score points, SD = 22 score points). Additionally, Chi-square test of independence showed that the subgroup of children with CIs also entailed statistically significantly higher number of children with non-age appropriate articulation relative to the NHC (chi-square test of independence, $X^2$ = 7.659, df = 1, p = 0.01). A pattern similar to the one obtained in the chronological age sample analysis, despite the older chronological age of the children with CIs in the subgroup analysis.

The accuracy percentage performance on the sonority-treated lexical perception task ranged between 69.9%- 100% for the NHC subgroup, and 83%-100% for the children with CIs subgroup. Median accuracy percentage performance was 91% for the NHC subgroup and 94% for the children with CIs. Pairwise comparison using Mann-Whitney test showed that both subgroups of children did not score statistically significantly different ($U = 61$, $df = 23$, $p = 0.507$) on the sonority-treated lexical perception task, as is illustrated in Figure 8. This result is similar to the one obtained from chronological age sample analysis.

Within group comparisons showed no main effect of the sonority condition on accuracy performance for the NHC subgroup, and a statistically significant effect of sonority condition on the accuracy performance ($\chi 2$ (3) = 9.109, $p = 0.028$) for the children with CIs. Further Pairwise comparison using Wilcoxon test showed statistically significantly higher performance in SS-SS condition relative to NS-NS condition ($Z = -2.236$, $p = 0.025$) and NS-SS condition ($Z = -2.121$, $p = 0.034$) in children with CIs subgroup. Once again this result is similar to the one obtained from chronological age sample analysis.

Across group comparisons showed no statistically significant differences in the performance between both children subgroups on any of the sonority conditions [NS-NS ($U = 72$, $df = 23$, $p = 1.000$)], NS-SS ($U = 62.5$, $df = 23$, $p = 0.506$)], SS-NS ($U = 65.5$, $df = 23$, $p = 0.514$), SS-SS ($U = 54$, $df = 23$, $p = 0.07$)]. This result is also similar to the one obtained from chronological age sample analysis. It is worth noting that the children with CIs appear to score with extreme high accuracy on the SS-SS condition when matched according to the oral-language exposure period. All children within the CIs subgroup scored 100% percent correctly here, compared to 75% of the normal-hearing subgroup of children. Subgroup performance within and across the different sonority conditions is shown in Figure 9.

There were no statistically significant differences between the two children groups on the RT of the rabbit-visual task [t (14.333) = 1.459, p = 0.159], and on the sonority-treated lexical perception task [t (22) = 0.137, p = 0.892], as depicted in Figure 10. These results are different from the results obtained when comparing children groups of chronological age, where the children with the CIs were statistically significantly slower than the NHC as an overall and on SS-SS condition. Further exploration of the RT on the different sonority conditions using independent-samples *t* tests confirmed that both subgroups did not differ in RTs across the different sonority conditions [NS-NS [t (16.157) = 0.507, p = 0.619], NS-SS [t (22) = -0.281, p = 0.789], SS-NS [t (17.787) = 0.248, p = 0.807], even for the condition SS-SS [t (14.333) = 0.038, p = 0.970]. The RT on the different sonority conditions across the children subgroups is shown in Figure 11.

## DISCUSSION

Sonority, as a phonetic/phonological cue, is relatively understudied in the population of children with CIs. Previous research has focused on studying the production of SSP-violating stimuli, rather than on studying the influential effect of sonority on speech perception and lexical access of children with CIs. To our knowledge, there are no studies that have evaluated the role of sonority on lexical perception and access of phonotactically-legal sequences in prelingually deafened children with CIs. In the current study, the various sonority conditions; NS-NS, NS-SS, SS-NS, and SS-SS were studied to explore the interactive effect of sonority's perceptual prominence versus SSP on the degree of lexical access, while probing for the possible underlying processing and language mechanisms that influence lexical access in children with CIs.

The high overall accuracy scores observed in the current study by all groups was expected, since individuals in the study had a minimum hearing age of 2 years. According to Carey and Bartlett (1978) the fast mapping of words onto meanings is achieved during that age period, with a capability of acquiring words at a very rapid rate, on the order of 10 to 20 new words a day.

The following research questions were addressed in the current study with an ultimate goal to provide knowledge that can be used in optimizing auditory input access and improving learning strategies for children with CIs.

**Research Question 1- How do sonority-related parameters affect the degree of lexical perception in children with CIs, relative to NHC and NHA?**

In the current study, children with CIs performed as accurately as the NHC on each of the sonority conditions and as an overall score. Winn et al. (2011) has highlighted that under conditions of normal redundancy of acoustic cues, individuals with CIs could potentially achieve equally accurate performance on speech recognition tasks as the normal-hearing individuals. However, more importantly, CI users most probably use different acoustic cues to achieve such equally accurate performance. Pattern differences were observed when comparing the performance of each of the children groups to those of adults. Children with CIs performed adult-comparable “only” on the highly sonorous SS-SS condition, while the NHC scored equally well to NHA on all conditions apart from the NS-NS condition. This demonstrates that children with CIs were able to learn and identify words relying on perceptual prominence cues of highly sonorous segments with high, adult-equivalent accuracy.

In terms of RTs, a statistically significantly longer RT on SS-SS condition was required by the children with CIs relative to the NHC. A possible explanation is that the hearing impaired individual must invest extra effort to achieve perceptual success (Baddeley 1996; Pichora-Fuller etal. 2016). This comes at the expense of processing resources that could have been available for encoding the speech content in memory. However, a token effect was not ruled out for this SS-SS condition, meaning that the longer RT maybe also attributable to the specific token “mola”. Yet, two out of the three other tokens within the SS-SS condition showed also longer RT.

The answer to the first research question is therefore: both groups of children perform equally accurate on the lexical perception task as an overall and on the different sonority-related parameters. Differences in performance are detected when comparing both groups to the adult group, where the children with CIs show adult- equivalent accuracy on the SS-SS condition only. This higher accuracy performance on perceptually prominent lexical segments comes at the expense of processing resources as expressed by the longer RTs.

**Research Question 2- Do children with CIs perform better in lexical tasks by relying on perceptual prominence cues brought about by highly sonorous lexical segments or do they rely on language learning rules evidenced by sonority sequencing cues?**

The first research question showed that children groups performed equally accurate on the different sonority conditions. However, they may utilize cues in a different manner to achieve such equally accurate performance. This has been demonstrated through the within group comparison where an effect of the sonority-related parameters on the degree of lexical perception of children with CIs was demonstrated. Within group comparisons showed that children with CIs were able to learn and identify words relying on perceptual prominence cues of highly sonorous segments with high accuracy. This was evidenced through their statistically more accurate performance on SS-SS condition relative to the optimal-SSP onset syllable conditions (NS-NS and NS-SS). On the other hand, the NHC performed equally well on all conditions regardless of the sonority of the speech signal.

The consistent superior accuracy performance on the sonority condition SS-SS in children with CIs is evident through the within group comparison, as well as the adult comparable performance on that condition solely. Sonority influences speech perception through the perceptual prominence cues, as well as through the language learning rule of SSP. According to the auditory sensitivity hypothesis (Sussman 1993, 2001) the relatively immature auditory system of younger children, in terms of anatomical and neurological structures, is responsible for children relying more on louder, longer duration cues (Ohde & Haley 1997; Sussman 2001). In children with CIs, the reduced auditory sensitivity may cause them to display this pattern of immaturity even at an older age. This causes them to rely on louder cues, which explains the high accuracy on the SS-SS word template. Thus children with CIs were expected to detect the cues provided by the perceptual prominence of highly sonorous segments, given that they have restored audibility through the CIs, and are documented to have intact temporal processing (Shannon 1989, 1992). On the other hand, their ability to process and develop the phonological grammar rules of the universally employed SSP was expected to be hindered or delayed, as a result of exposure to periods of auditory input deprivation and/or relative degradation of the auditory signal. An optimal SSP for CV syllables was present in segments with non-sonorous consonants, to allow for a greater degree of rise from the onset to the nucleus of the syllable. Thus, children with CIs were expected to tap into the perceptual prominence cues in syllables with high sonority (SS syllable), better than syllables with low sonority that lack the perceptual prominence, and rely on SSP (NS syllable).

Furthermore, Kuhl et al. (2008) points out that the infrequent or non-occurring category contrasts in a language could lead to the fading of discriminatory attention for the less-represented contrasts. This could be accompanied by a perceptual narrowing of categories that occurs with experience. For children with CIs, the reduced or degraded audibility of NS contrasts versus SS contrasts could mean that the NS syllable is considered an infrequent representation, with subsequent fading and further sharpening of the SS syllables.

So, the answer to the second question would be that children with CIs perform better in lexical tasks by relying on sonority contour perceptual prominence brought about by highly sonorous lexical segments. This is in line with them being exposed to periods of relative auditory deprivation and degradation of signal input.

**Research Question 3- Do NHC perform differently on sonority-driven perceptual prominence cues versus language dependent cues, and is performance comparable to NHA?**

The NHC were capable of utilizing both the perceptual prominence cues and the language dependent cues of SSP. This is evident through performing equally well on all sonority conditions, even in the condition with the lowest sonority perceptual prominence as in the condition of NS-NS.

Nevertheless, such capability of utilizing SSP-cues is not as well-developed as in adults. This is expressed through the lower accuracy performance of the NHC relative to the NHAs on the NS-NS condition. For NHC, the presence of one syllable with sonority perceptual prominence cue, regardless of position; SS-SS, SS-NS, NS-SS was sufficient to make them score adult-like. This means that NHC continue to rely on sonority perceptual prominence cues to an extent. However, the magnitude of reliance on such prominence cues by NHC is less than that of children with CIs, as evidenced by the adult-like accuracy performance on intermediate conditions. This brings us back to the auditory sensitivity hypothesis (Sussman 1993, 2001) where information processing in young children is affected by salience, loudness or longer duration cues (Ohde & Haley 1997; Sussman 2001).

Gómeza et al. (2014) investigated whether the newborn brains display a predisposition to the SSP by using functional near infrared spectroscopy (Gervain 2011; Lloyd-Fox et al. 2010; Rossi et al. 2012). Results showed that the brain responses of the newborns reacted to syllables like blif, bdif, and lbif in a manner consistent with adults' patterns of preferences, despite having little to no linguistic experience. They concluded that sonority-related bias in humans does not require extensive linguistic experience or ample practice with language production. In the current study, the fact that NHC scored less accurately than the NHA only on the NS-NS condition guide us to think that SSP is a learnable principle rather than being purely innate.

This is particularly important, as such a notion of SSP being learnable, would open the way for auditory rehabilitation tools that aim to abolish the static template-driven word learning and enhance the lexical access performance across different sonority conditions in children with CIs. Such tools would focus on training the auditory input through frequent presentation, as in children the representation of word forms that are frequently heard becomes more robust (Vihman 2016).

The answer to research question 3 is that NHC do not perform differently on sonority-driven perceptual prominence cues versus language dependent cues, as they are able to utilize both. However, they fall behind the NHA on NS-NS condition. A condition that is challengeable in terms of perceptual prominence and requiring the high dependency on SSP. This leads to the assumption that SSP is a learnable principle.

**Research Question 4- Do children with CIs vary in lexical access strategies relative to their normal-hearing peers, being exposed to periods of relative auditory deprivation and relatively degraded auditory signal input?**

Children with CIs appear to adopt an early word-learning strategy termed template-driven (SS-SS) word learning. In typically developing children, the whole-word learning is an early word learning strategy that spurs further vocabulary acquisition within a lexicon. However, this strategy doesn't continue in later stages of development, as the child eventually comes to master more complex adult sequences of articulation, speech planning and memory representation. Moreover, the template shape itself is dynamic rather than being static to a single form (Vihman & Keren-Portnoy 2013). The SS-SS word template, being highly perceptually prominent amidst a period of auditory deprivation makes it fit as an ideal learnable template.

The subgroup analysis attempted to answer the question whether children with CIs when exposed to language for equal periods as normal- hearing children would still adopt the deviant word-learning strategy, or whether they would adopt similar strategies to the NHC. However, it is important to note that even though children are matched on hearing age, the actual oral language exposure of the children with CIs is not essentially equivalent to that of the NHC. This is because the children with CIs are exposed to degraded hearing experience via electric stimulation, as opposed to acoustic hearing available to NHC.

In terms of accuracy performance, results showed that whether children groups are matched according to the oral-language exposure period or chronological age, they still exhibit the same pattern of superior performance on SS-SS condition relative to NS-starting conditions. NHC subgroup continued to show equal performance across all conditions. It thus appears that even with matching of the oral-language exposure period, the children with CIs still employ a deviant strategy compared to the NHC. It is important to note that whether according to the chronological or hearing age, children with CIs had statistically lower receptive vocabulary scores, and greater number of children with non-age-appropriate articulation relative to the NHC. This shows that even with equivalent oral-language exposure period, children with CIs in the current sample had a less developed language relative to the NHC which is in line with the hypothesis of delayed/hindered language learning rule of SSP.

Furthermore, the template-driven word learning strategy appeared to be more evident when children with CIs were matched with NHC in hearing age. This was demonstrated by the consistent high accuracy score of 100% on the SS-SS condition obtained by all children with CIs in the subgroup analysis. Furthermore, children with CIs showed statistically equivalent RT on the SS-SS condition when matched in hearing age but not chronological age. That is, the children with CIs show increased proficiency and less effortfullness on the preferable template SS-SS, when matched in hearing age.

Another interesting finding in the current study was that the lexical access in children with CIs appeared to be partially driven by the initial segment of the word, as demonstrated by the statistically superior performance on SS-SS condition relative to conditions that start with an NS syllable but not SS syllable. Yet, performance is not solely driven by the initial syllable or else a statistically significant difference between SS-NS condition and conditions beginning with NS should have been observed as well. Jusczyk et al. (1999), suggest that paying attention to the beginning of words is a useful strategy for early word learners. It could be that children with CIs are employing the template driven word learning along with a specific onset-emphasis strategy. However this is unlikely as the two strategies occur in different developmental stages in the normal-hearing individuals rather than concomitantly. The current study involved a wide age range of tested children with CIs; 4 ; 11 – 15 ; 2. It is thus possible that some of the children in the sample are adopting a template driven word learning strategy, while others are segmenting the word with emphasis on the initial syllable. Future work studying the effect of sonority conditions across the different age groups could provide a deeper insight.

The current study RT analysis has provided additional evidence that oral-language exposure period is a key factor in developing the auditory processing skills for the children with CIs. Children with CIs showed statistically significantly longer RTs relative to their normal-hearing peers on the sonority auditory task as an overall, and on SS-SS condition. In a previous study by Grieco-Calub et al. (2009), the RT of spoken word recognition in quiet in two-year-old children with CIs was longer than age-matched NHC. Reaction time was assessed using digital recordings of eye movements to target objects. Grieco-Calub et al. (2009) concluded that the auditory experience, or hearing age of young CI users prolongs the time course of spoken word recognition abilities. In our study, this was further supported by the subgroup analysis, which yielded similar RTs when NHC and children with CIs were matched according to the oral-language exposure period/ hearing age.

The answer to research question 4 is that children with CIs vary in lexical access strategies relative to their normal-hearing peers. The current study sample of children with CIs with age range 4 ; 11 – 15 ; 2 adopt a template-driven word learning pattern, an early stage word learning strategy, following the template SS-SS with possible partial/alternative word onset emphasis. The early word-learning strategies were still adopted in lexical access of children with CIs even with matching of the hearing/ oral-language exposure period. Oral-language exposure period is a key factor in developing the auditory processing skills, in terms of effortfullness and RTs.

## Conclusions

An effect of the sonority-related parameters on the degree of lexical perception of children with CIs was demonstrated. Children with CIs perform better in lexical tasks relying on sonority perceptual prominence brought about by the highly sonorous lexical segments within the sonority condition SS-SS. They adopt an early stage word learning strategy known as template-driven word learning. The sonority condition SS-SS in individuals known to have restored audibility and good temporal processing makes it an adequate lexical template choice. In the current study broad age sample, lexical access was partly driven by the initial syllable in children with CIs, another early word learner's strategy, as evident by the superior performance on SS-SS condition relative to NS-initial words only. Template-driven word learning strategy has a predominant role in lexical access of children with CIs even when matched to NHC on the hearing/ oral-language exposure period. NHC demonstrate their ability to shift between and utilize both types of sonority cues, namely perceptual prominence and SSP. The lexical access performance in NHC of the current sample is not template-driven. Compared to the NHA, the NHC rely on perceptual prominence cues but to a lesser extent than children with CIs indicating the developmental nature of perceiving the SSP cue during phonological acquisition. .

## Future Work

Cross linguistic studies -- controlling for token effect a priori -- would validate the outcomes of the current study addressing a language-universal rule. Further probing of the possible underlying causes of the variation in performance of children with CIs relative to normal-hearing individuals will provide a way to inform clinical practice and guide intervention. Studying different age groups of preschoolers and school-aged children will allow defining of the specific strategies employed of template word learning versus initial syllable preference. It may also provide insights to the developmental pattern of SSP. Longitudinal studies that monitor the progress of children with CIs are the ultimate method to observe the developmental effect. This collective knowledge would allow the creation of an evidence-based auditory rehabilitation tool that employs sonority conditions as a pillar on which further new advances could be built. Such optimization of the performance across the different sonority conditions in children with CIs is expected to aid in their lexical access and language development outcomes.


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## Figure Legend

**Figure 1:** Flow chart of the Sonority Experiment Trial

**Figure 2**: Praat waveform, spectrogram and intensity contour of the token /vamo/ with demarcation of the phoneme boundaries and the sound peak minima of consonants.

**Figure 3:** Bar chart comparing the receptive vocabulary score performance across children test groups. Different letters (a, b) indicate significant differences across groups according to one-way ANOVA at $p < 0.05$.

**Figure 4:** Box plot comparing the median accuracy percent correct scores and interquartile ranges of the sonority-treated lexical perception task in the three different experimental groups. Different letters on comparison between groups indicate significant differences according to Mann-Whitney *U* test at $p < 0.05$. Horizontal Line indicates chance level.

**Figure 5:** Cluster Bar chart comparing the sonority accuracy percent correct score on the different sonority conditions within and across test groups. Different letters (a, b) indicate significant differences across groups for each sonority condition according to Mann-Whitney *U* test at $p < 0.05$. Brackets denotes significant differences between sonority conditions within each test group according to Wilcoxon at $p < 0.05$ (*) and $p < 0.01$ (**).

**Figure 6:** Bar chart comparing the visual and sonority-related average reaction time in msec (mean and SD) across the three groups. Different letters across groups indicate significant differences for the visual and the sonority task reaction times separately, according to post hoc tests with Bonferroni correction at $p < 0.05$.

**Figure 7:** Cluster Bar chart comparing the reaction time in msec (mean and SD) on the different sonority conditions across test groups. Different letters within each sonority condition indicate significant differences between experimental groups according to post hoc test with Bonferroni correction at $p < 0.05$.

**Figure 8:** Box plot comparing the median accuracy percent correct scores and interquartile ranges of the sonority-treated lexical perception task in the children subgroups matched according to oral-language exposure period. There are no statistically significant differences according to Mann-Whitney *U* test at $p < 0.05$ between subgroups. Horizontal Line indicates chance level.

**Figure 9:** Cluster Bar chart comparing the sonority accuracy percent correct score performance on the different sonority conditions across and within children subgroups matched according to oral-language exposure period. Different letters (a, b) indicate statistically significant differences between sonority conditions within each children subgroup according to Wilcoxon at $p < 0.05$. There are no statistically significant differences across groups for each sonority condition according to Mann -Whitney *U* test at $p < 0.05$

**Figure 10:** Bar chart comparing the visual and sonority-related average reaction time in msec (mean and SD) across the children subgroups matched according to oral-language exposure period age. There are no statistically significant differences on visual and sonority task reaction times separately according to independent-samples *t* tests at $p < 0.05$.

**Figure 11:** Cluster Bar chart comparing the reaction time in msec (mean and SD) on the different sonority conditions across the children subgroups matched according to oral-language

exposure period. There are no statistically significant differences across the subgroups according to independent-samples *t* tests at $p < 0.05$

## Supplemental Digital Content

Supplemental Digital Content 1.doc

Supplemental Digital Content 2.doc

Figure 1

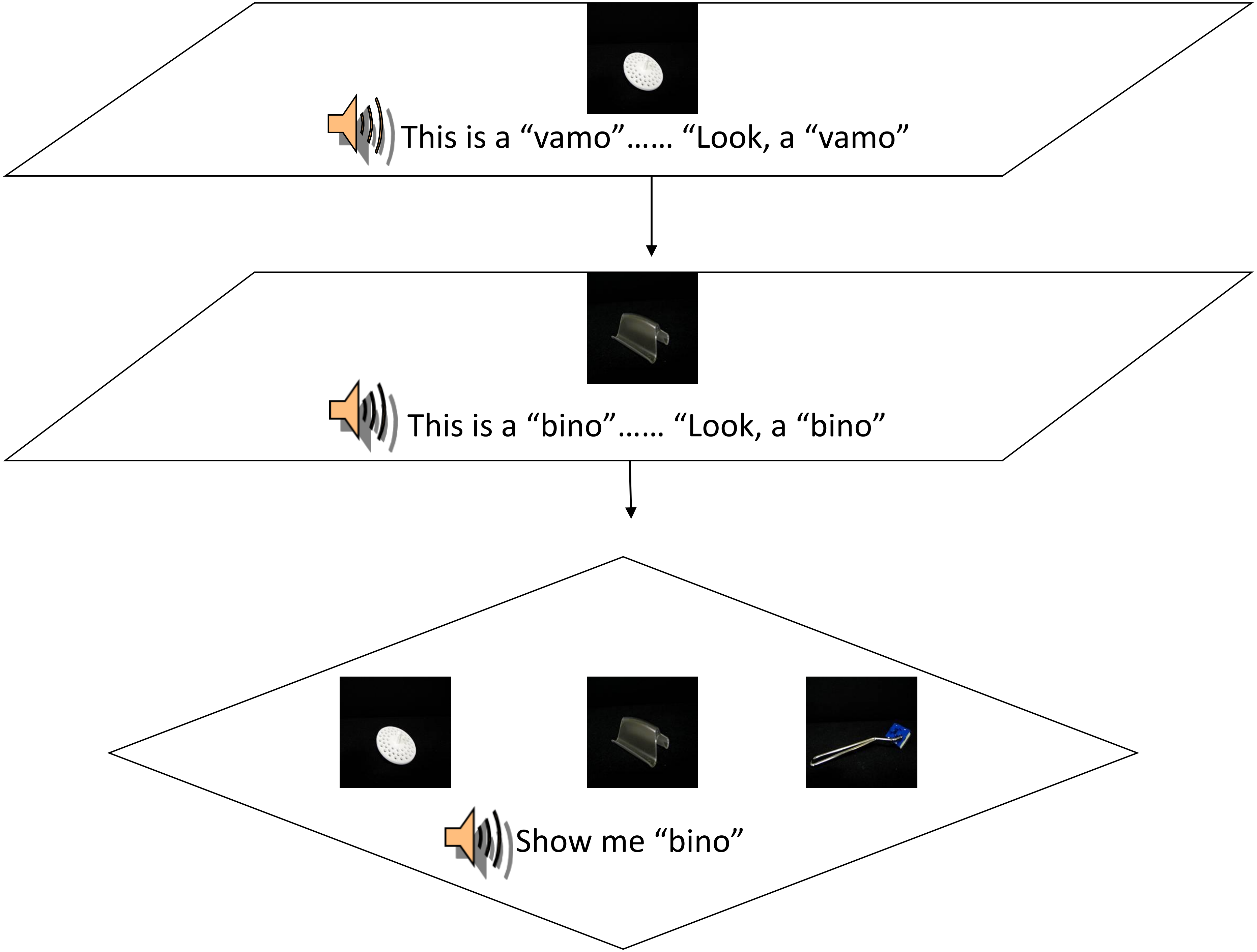

This is a “vamo”...... “Look, a “vamo”
This is a “bino”...... “Look, a “bino”
Show me “bino”

Figure 2

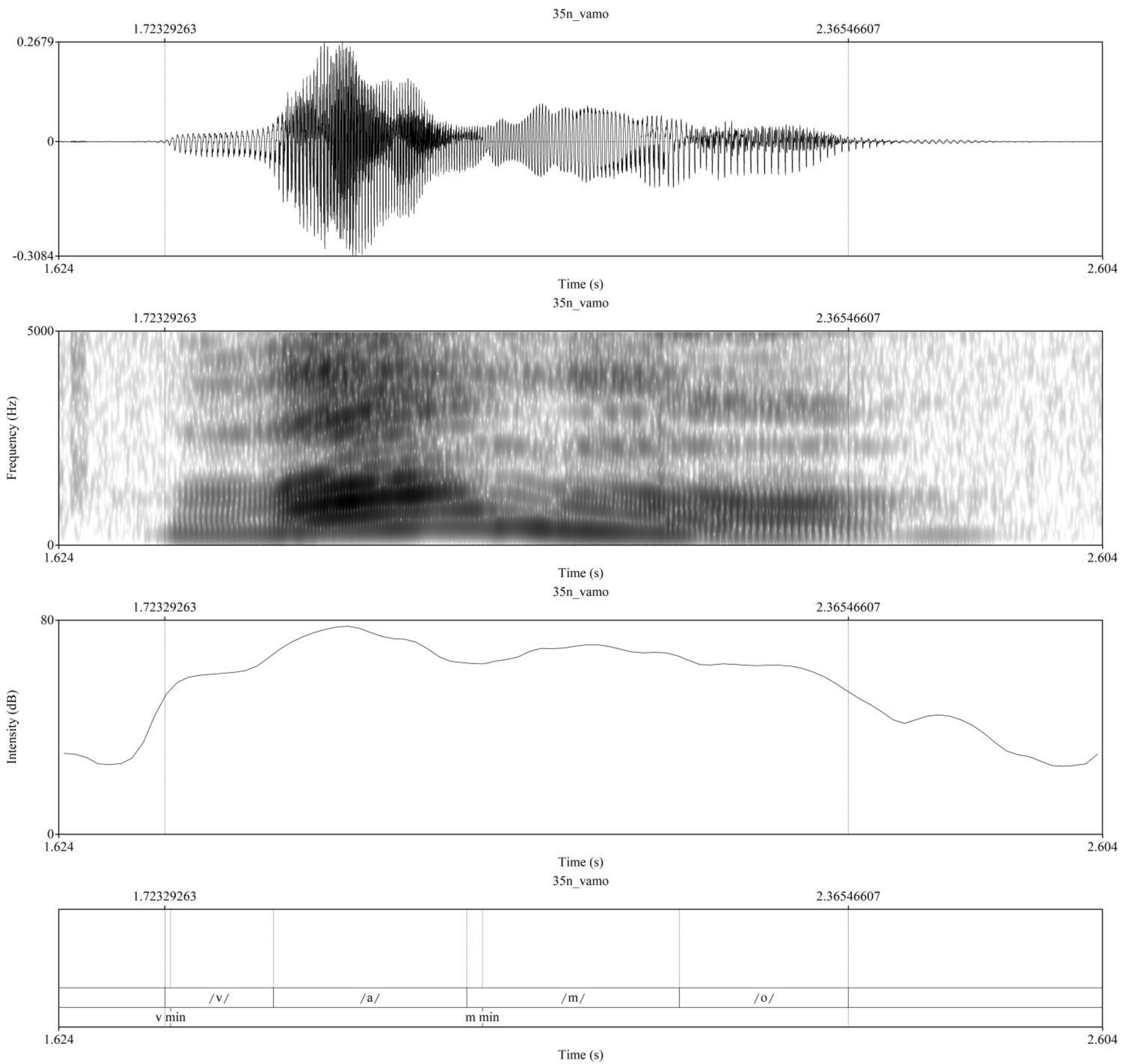

35n_vamo
1.72329263
2.36546607
0.2679
0
-0.3084
1.624
2.604
Time (s)
5000
Frequency (Hz)
80
Intensity (dB)
/v/
/a/
/m/
/o/
v min
m min

Figure 3

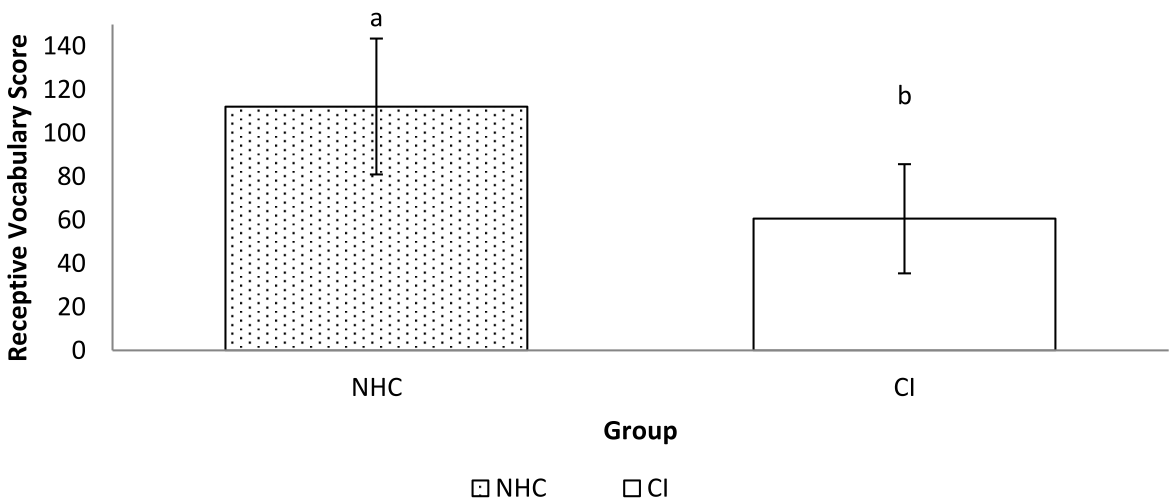

a
b
Receptive Vocabulary Score
0
20
40
60
80
100
120
140
NHC
CI
Group
NHC
CI

Figure 4

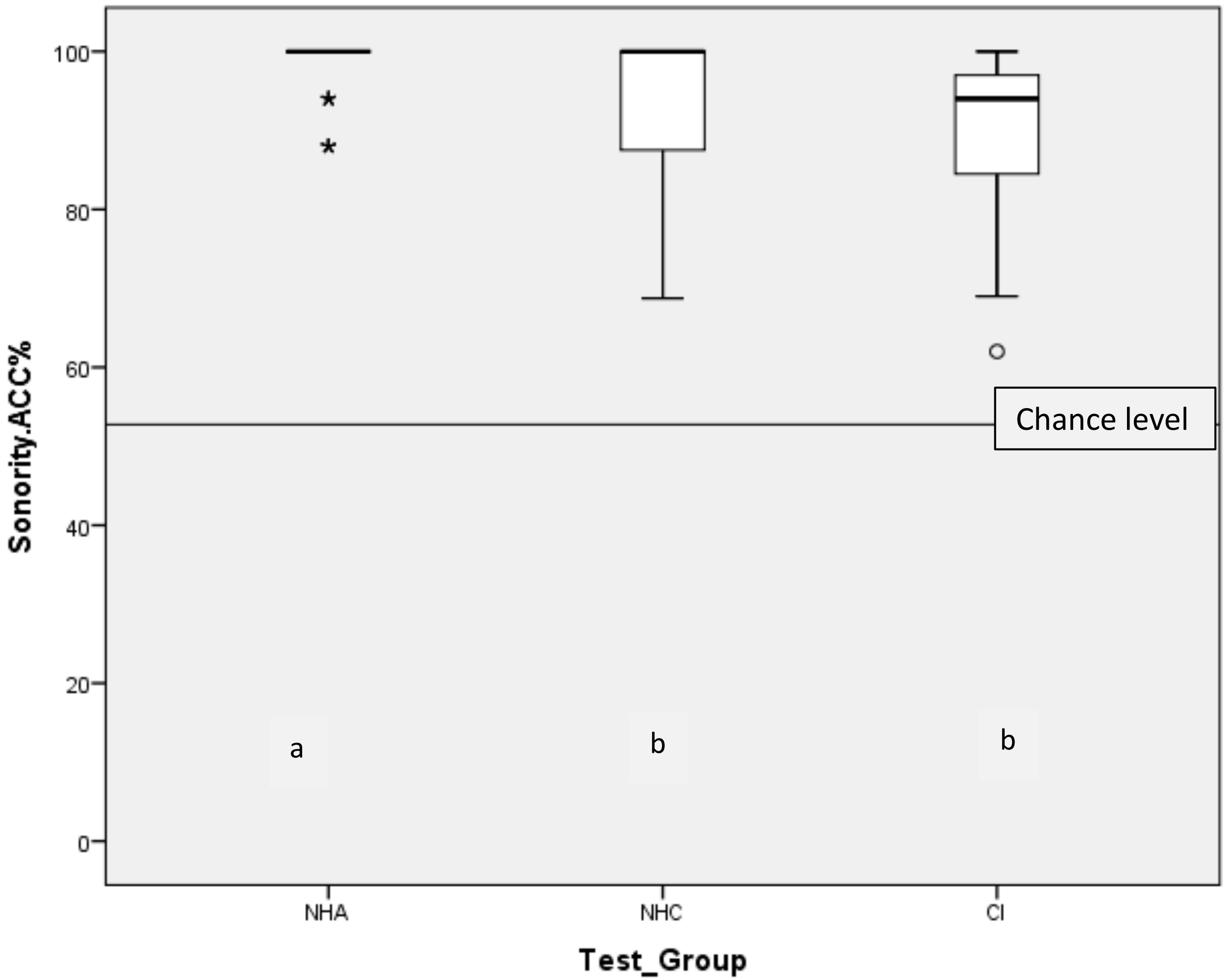
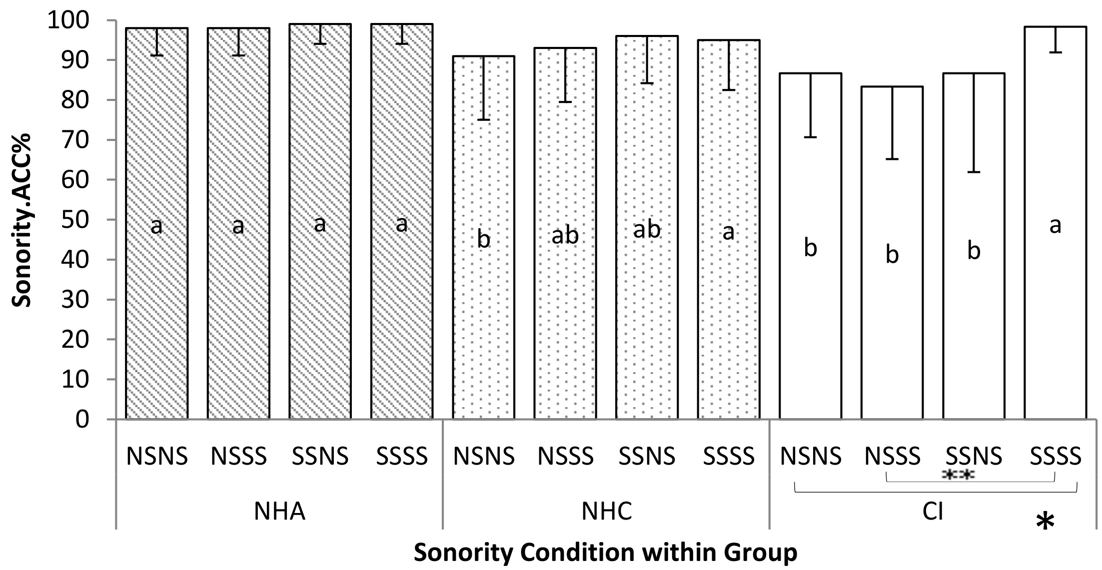

Sonority.ACC%
100
80
60
40
20
0
a
b
b
Chance level
NHA
NHC
CI
Test_Group

Figure 5



Sonority.ACC%
100
90
80
70
60
50
40
30
20
10
0
a
a
a
a
b
ab
ab
a
b
b
b
a
NSNS
NSSS
SSNS
SSSS
NSNS
NSSS
SSNS
SSSS
NSNS
NSSS
SSNS
SSSS
**
NHA
NHC
CI
*
Sonority Condition within Group

Figure 6

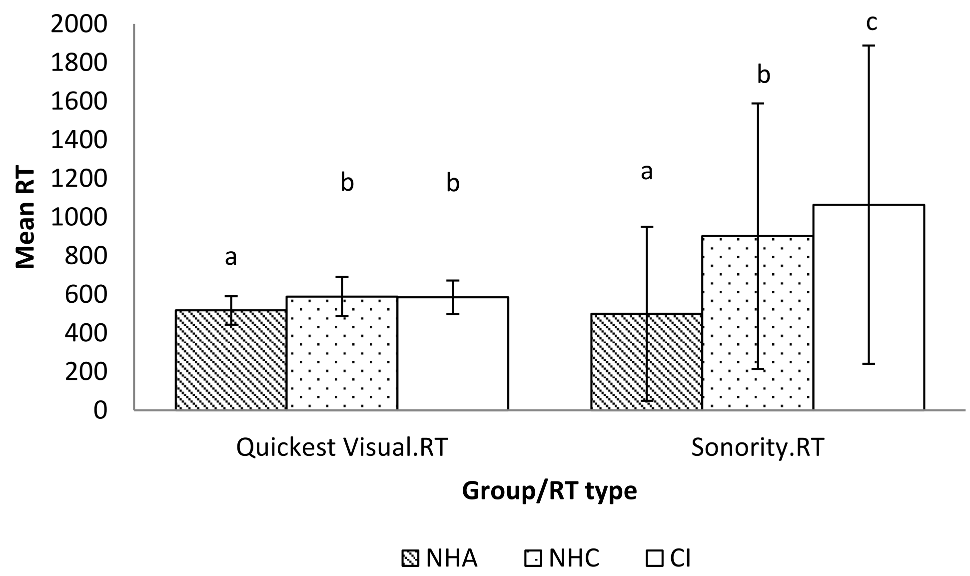

Mean RT
2000
1800
1600
1400
1200
1000
800
600
400
200
0
a
b
b
a
b
c
Quickest Visual.RT
Sonority.RT
Group/RT type
NHA
NHC
CI

Figure 7

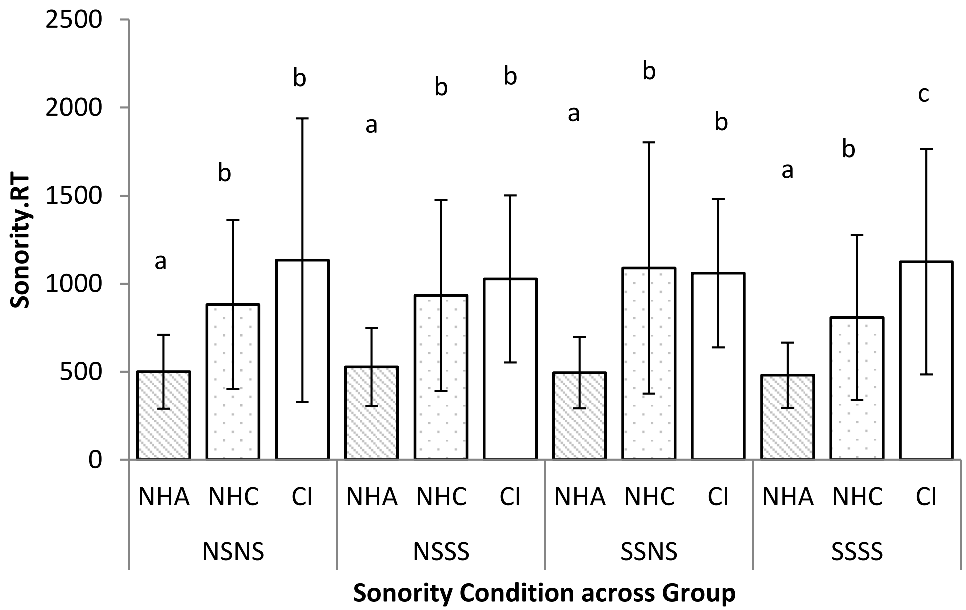

Sonority.RT
2500
2000
1500
1000
500
0
a
b
b
a
b
b
a
b
b
a
b
c
NHA
NHC
CI
NHA
NHC
CI
NHA
NHC
CI
NHA
NHC
CI
NSNS
NSSS
SSNS
SSSS
Sonority Condition across Group

Figure 8

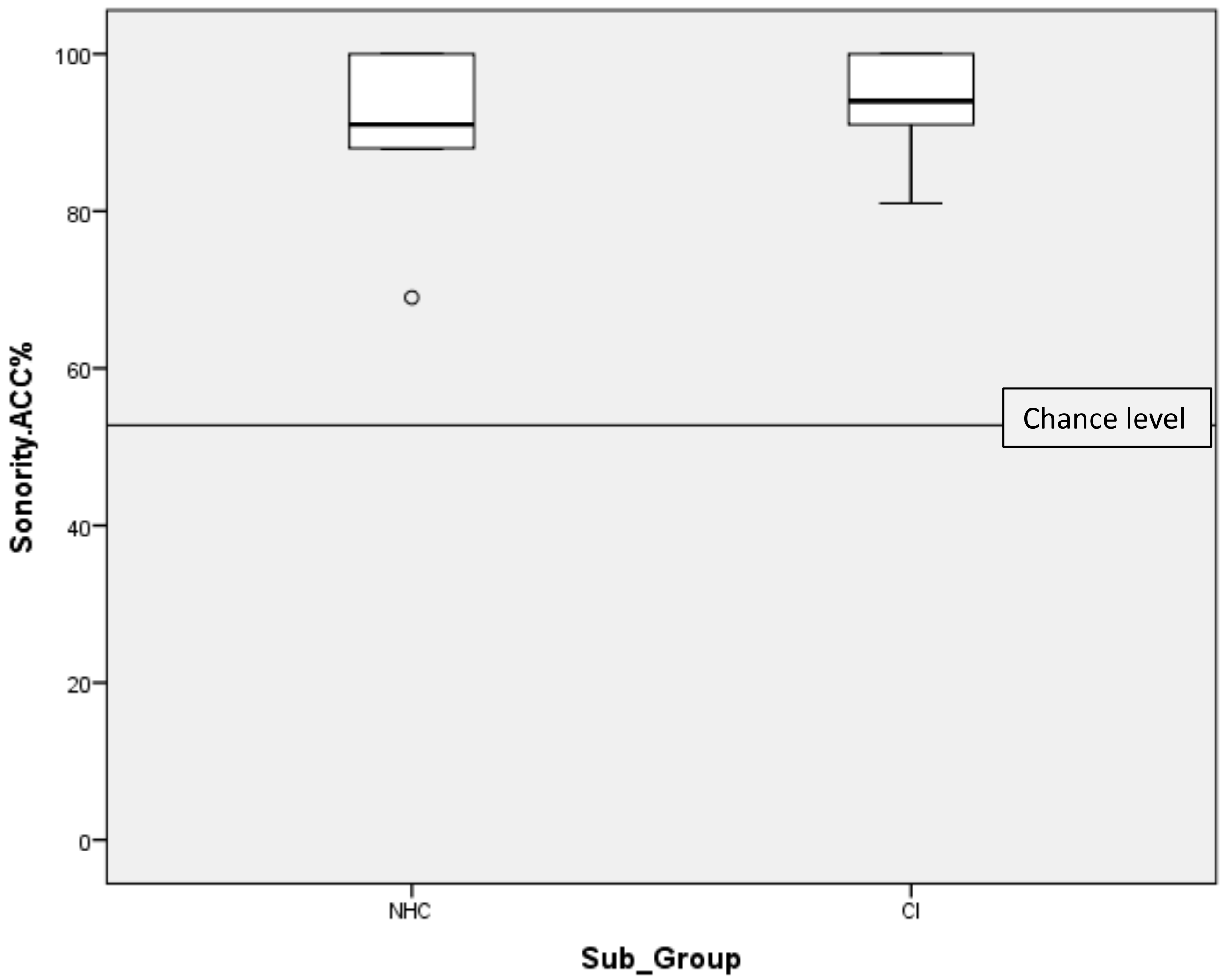


Figure 9

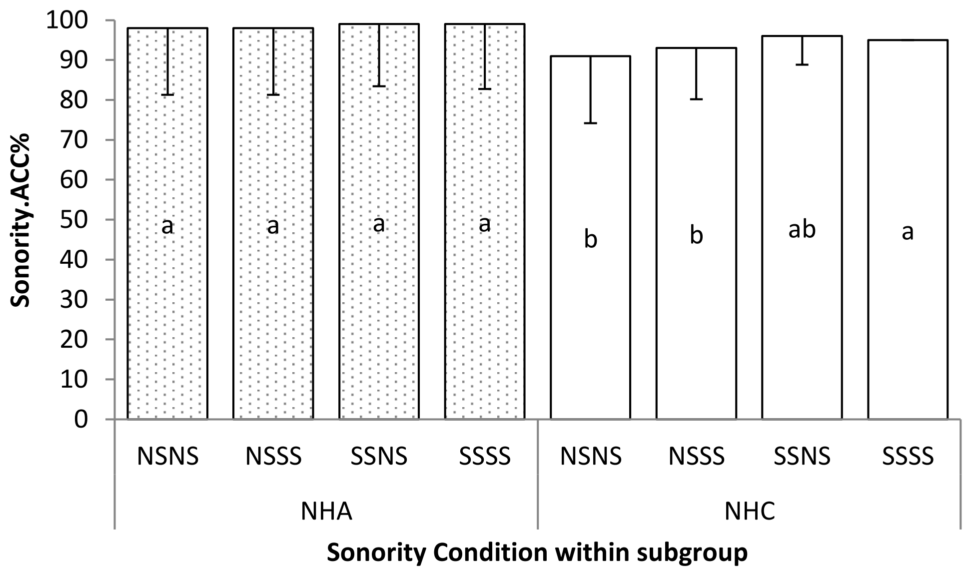
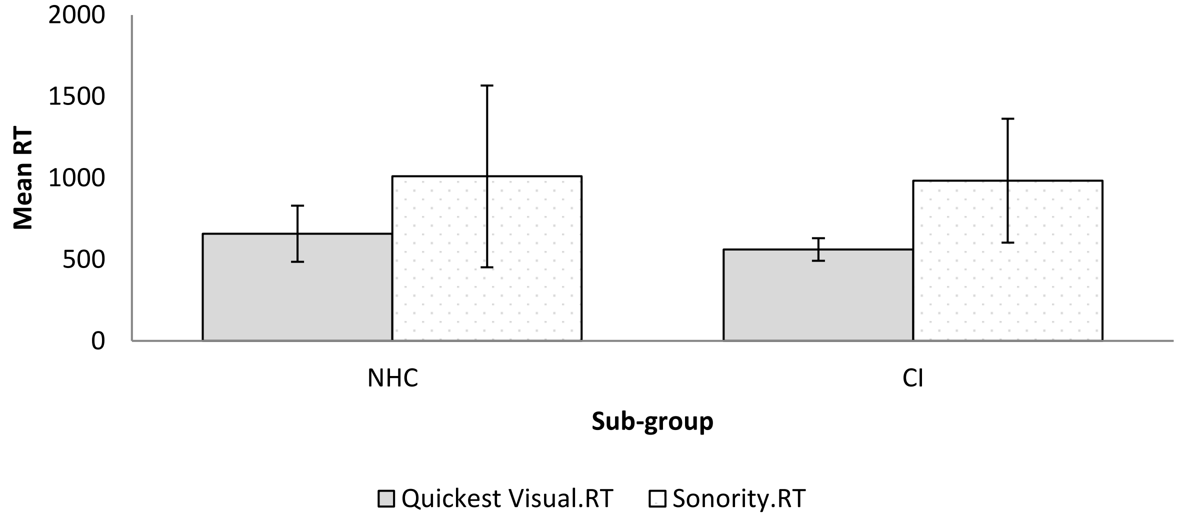
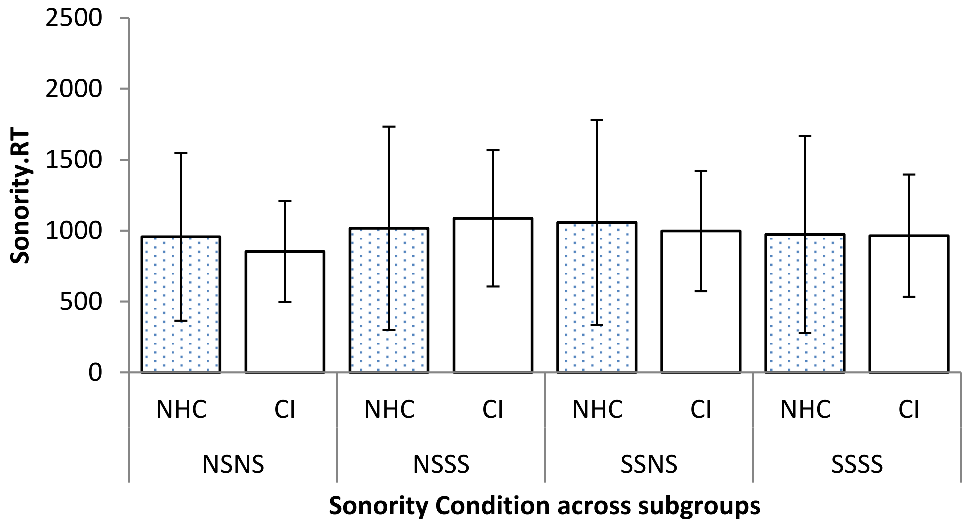

Sonority.ACC%
100
90
80
70
60
50
40
30
20
10
0
a
a
a
a
b
b
ab
a
NSNS
NSSS
SSNS
SSSS
NSNS
NSSS
SSNS
SSSS
NHA
NHC
Sonority Condition within subgroup

Figure 10



2000
1500
1000
500
0
Mean RT
NHC
CI
Sub-group
Quickest Visual.RT
Sonority.RT

Figure 11


Sonority.RT
2500
2000
1500
1000
500
0
NHC
CI
NHC
CI
NHC
CI
NHC
CI
NSNS
NSSS
SSNS
SSSS
Sonority Condition across subgroups

Table

**Table 1: Demographic Data of Children with CIs**

Age, Post-implant age, Aided free-field pure-tone average thresholds (500 Hz-2 kHz), and speech audiometry correct percent scores (word and sentence) of the children with CIs

| **Subject No.** | **Age** | **Postimplant Age** | **Free-Field PTA dB HL Thresholds** | **Speech Audiometry Correct %** | |
|---|---|---|---|---|---|
| | | | | **Word** | **Sentence** |
| 1 | 4 ; 11 | 2 | 22 | 98 | 94 |
| 2 | 5 ; 7 | 3; 1 | 17 | 84 | 78 |
| 3 | 5; 0 | 3; 1 | 12 | 98 | 92 |
| 4 | 6 ; 1 | 3; 2 | 22 | 68 | 44 |
| 5 | 6 ; 2 | 4; 1 | 15 | 88 | 92 |
| 6 | 6 ; 2 | 4; 10 | 22 | 76 | 80 |
| 7 | 8 ; 11 | 6 | 17 | 98 | 96 |
| 8 | 9 ; 4 | 6; 6 | 20 | 100 | 100 |
| 9 | 8 ; 5 | 7; 8 | 12 | 96 | 98 |
| 10 | 10 ; 9 | 7; 11 | 13 | 98 | 92 |
| 11 | 10 ; 7 | 8; 8 | 8 | 98 | 100 |
| 12 | 11 ; 7 | 9; 1 | 12 | 44 | 70 |
| 13 | 14 ; 8 | 11; 8 | 13 | 100 | 98 |
| 14 | 14 ; 3 | 12; 1 | 12 | 100 | 100 |
| 15 | 15 ; 2 | 12; 8 | 13 | 100 | 100 |
| **Mean** | 9; 2 | 6; 10 | 15 | 90 | 89 |
| **Sd** | 3; 7 | 3; 6 | 4.312526359 | 16.01546871 | 15.43403783 |

**Table 2: Sonority Experiment Inventory**

| Sonority condition | Consonant content | Word stimuli |
|---|---|---|
| NS-NS | voiceless fricative+ voiced stop | θigo |
| | voiceless stop+ voiced fricative | tiJe |
| | voiced fricative+ voiceless fricative | vuse |
| | voiced stop+ voiceless stop | buci |
| NS-SS | voiceless fricative+ lateral | falu |
| | voiceless stop+ flap | ture |
| | voiced fricative+ nasal | vamo |
| | voiced stop+ nasal | bino |
| SS-NS | laterals+ voiceless fricative | lufo |
| | flap+ voiceless stop | retu |
| | flap+ voiced fricative | reJi |
| | nasals+ voiced stop | mugo |
| SS-SS | lateral+ nasal | lamo |
| | flap+ lateral | riλa |
| | nasal+ lateral | mola |
| | nasal+ flap | noru |

**Table 3: Intensity minima values of sonorous versus non sonorous consonants within the non-real CV-CV word stimuli, arranged ascending, per syllable position.**

| Non Sonorous C1 | dB min | Sonorous C1 | dB min | Non Sonorous C2 | dB min | Sonorous C2 | dB min |
|---|---|---|---|---|---|---|---|
| /f/ in falu | 31.36 | /r/ in reJi | 57.359 | /c/ in buci | 36.892 | /l/ in falu | 61.845 |
| /θ/ in θigo | 37.659 | /r/ in retu | 57.61 | /t/ in retu | 37.452 | /m/ in vamo | 62.859 |
| /v/ in vuse | 38.569 | /n/ in noru | 58.755 | /f/ lufo | 46.829 | /r/ in noru | 64.775 |
| /t/ in tiJe | 40.328 | /r/ in riʎa | 60.022 | /g/ in θigo | 50.107 | /ʎ/ in riʎa | 66.367 |
| /t/ in ture | 47.809 | /l/ in lamo | 60.191 | /J/ in tiJe | 50.231 | /r/ in ture | 67.257 |
| /b/ in bino | 51.29 | /m/ in mugo | 61.257 | /s/ in vuse | 50.935 | /m/ in lamo | 67.986 |
| /v/ in vamo | 53.988 | /l in lufo | 62.397 | /J/ in reJi | 51.855 | /l/ in mola | 68.174 |
| /b/ in buci | 58.25 | /m/ in mola | 64.879 | /g/ in mugo | 54.852 | /n/ in bino | 68.811 |
| Mean | 44.906625 | Mean | 60.30875 | Mean | 47.394125 | Mean | 66.00925 |
| Sd | 9.310951308 | Sd | 2.52534743 | Sd | 6.68606757 | Sd | 2.588898759 |

**Table 4: Intensity minima values of sonorous versus non sonorous consonants of real-Greek words**

| Token | Consonant1 | dB min | Consonant 2 | dB min |
|---|---|---|---|---|
| milo | /m/ | 54.662 | /l/ | 64.561 |
| gala | /g/ | 45.411 | /l/ | 63.141 |
| filo | /f/ | 39.014 | /l/ | 67.854 |
| poδi | /p/ | 41.625 | /δ/ | 49.935 |

**Table 5: The distribution of the age and gender of the different studied groups**

| Study Groups | | | | | | |
|---|---|---|---|---|---|---|
| | **NHA (n = 50)** | | **NHC (n = 25)** | | **CI (n = 15)** | |
| **Age** | | | | | | |
| Min. – Max. | 19;0 – 39;5 | | 3;9 – 15;2 | | 4;11 – 15;2 | |
| Median | 21;7 | | 7;11 | | 8;11 | |
| **Sex** | **%** | **No.** | **%** | **No.** | **%** | **No.** |
| Male | 48.0 | 24 | 48.0 | 12 | 53.3 | 8 |
| Female | 52.0 | 26 | 52.0 | 13 | 46.7 | 7 |

## Supplemental Digital Content 1

## The procedure of calculation and matching of CV syllables to medium frequency of occurrence.

Adamidou et al. (2013) database entailed lists of orthographic syllable frequencies and the syllabified phonemic word form transcriptions, along with ratings of frequency of their occurrence. First, all CV syllables were extracted from the database, with grouping of CV syllables according to IPA and recalculation of the frequency of occurrence, due to the multiple orthographic representation of a single phonemic transcription in Greek Language. Frequency of occurrences was then log 10 transformed due to the extremely wide range of values concerning the frequency of occurrences, with subsequent calculation of mean and standard deviation for each position. A criterion of one standard deviation (SD) from the mean was selected to denote medium frequency of occurrence for each of the positions. The criteria were exposed to further conservative restriction by taking the lower limit of the highest frequency and the higher limit of the lowest frequency for positions one and two.

**Supplemental Digital Content 2**

The acoustic analysis of the stimuli using Parker (2008) methodology

Measurements were done using PRAAT (Boersma & Weenink, 2016) in default setting of intensity calculations. First, the target word was selected and further segmented into the individual consonant components. Precaution was taken not to include in the selection the sound level protrusion of adjacent segments. For all consonants apart from stops, the measurement of the minimum dB value was performed by selecting the target consonant segment and then using the "get minimum intensity" function from the Intensity Tab on PRAAT. This was cross validated by visually inspecting the consonant segment and manually selecting the minimum point of the intensity contour and taking the intensity reading at that point. For stops, a different methodology of measurement was employed. According to Parker (2008), two minimum points should be measured and averaged; one corresponding to the occlusion phase and one for the ejective release. For the ejective phase, the same procedure was applied as Parker (2008) for the voiced and voiceless stops. The burst segment was selected and a sound level minimum was noted using the same function on PRAAT. However, for the occlusion phase a different occlusion phase segment was selected than the one denoted by Parker (2008). According to Parker (2008) the spectrogram selected for the occlusion phase included the final half of the carrier phrase vowel /a/ and the beginning of the first vowel of the CV-CV. In the current study, for the voiced stops, the occlusion phase segment was selected to entail the voicing bar only, since in Greek language the voicing bar prior to the burst is clearly evident, as voiced stops are pre-voiced (Botinis, Fourakis, & Prinou, 2000). For the voiceless stops, Parker (2008) methodology was applied for stops in the second position, however for initial stops it was not possible to measure the closure period since the target word and the carrier phrase in the current experiment are collated rather than being running speech. Therefore, the time frame of the voicing bar of the voiced stops was used to guide the demarcation of the occlusion phase for initial voiceless stops. The minimum was then denoted for the selected occlusion phase segment. The two minima; ejective and occlusive were then averaged, and the average reported as the minima value for the voiced stop. All measurements for stops were also cross validated by visual inspection.

**References:**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Botinis, A., Fourakis, M., & Prinou, I. (2000). Acoustic structure of the Greek stop consonants. *Glossologia 11*(12), 167-199.

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