ACOUSTIC AND ARTICULATORY CHARACTERISTICS OF MALAYALAM SPEAKING CHILDREN USING COCHLEAR IMPLANT

A DOCTORAL THESIS

Submitted to the University of Mysore
for the award of degree of
Doctor of Philosophy (Ph.D) in Speech-Language Pathology

by

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CERTIFICATE

This is to certify that the thesis entitled **“Acoustic and articulatory characteristics of Malayalam speaking children using Cochlear Implant”** submitted by Ms. Deepthy Ann Joy for the degree of Doctor of philosophy in Speech-Language Pathology, to the University of Mysore was carried out at the All India Institute of Speech and Hearing, Mysuru.

Place: Mysuru
Date: 02.11.2020

Prof. M. Pushpavathi
Director
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Mysuru-06

CERTIFICATE

This is to certify that the thesis entitled **“Acoustic and articulatory characteristics of Malayalam speaking children using Cochlear Implant”** submitted by Ms. Deepthy Ann Joy for the degree of Doctor of Philosophy in Speech-Language Pathology, to the University of Mysore was carried out at the All India Institute of Speech and Hearing, Mysuru, under my guidance. I further declare that the results of this work have not been previously submitted for any other degree.

Place: Mysuru
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DECLARATION

I declare that this thesis entitled **“Acoustic and articulatory characteristics of Malayalam speaking children using Cochlear Implant”** which is submitted for the award of the degree of Doctor of Philosophy in Speech-Language Pathology, to the University of Mysore, is the result of work carried out by me at the All India Institute of Speech and Hearing, Mysuru, under the guidance of Prof. N. Sreedevi, Professor of Speech Sciences, All India Institute of Speech and Hearing, Mysuru. I further declare that the results of this work have not been previously submitted for any other degree.

Place: Mysuru Deepthy Ann Joy
Date: 02.11.2020

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“I can do all things through him who strengthens me”

Philippians 4:13

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Abstract

Restoration of audition through a Cochlear Implant (CI) is established to have a significant benefit for individuals with hearing loss. Speech characteristics of children with cochlear implantation are reported to be approaching normal limits compared to children fitted with digital hearing aids. Since the phonetic or phonological characteristics vary across languages, it is important to replicate studies into other common spoken languages to provide language appropriate data for rehabilitation professionals working with CI. In the context of a highly well-executed CI scheme, 'Shrutitharangam' by the state government of Kerala, there is a steady increase in the number of children with hearing impairment undergoing CI surgery. Therefore, their effective speech rehabilitation plan should be on strong foundations of language appropriate evidence-based research. Further, there are no published Indian studies which provide detailed profiling of acoustics and articulatory characteristics in children using CI.

The present study aimed to investigate the acoustic and articulatory characteristics of Malayalam speaking children using CI in the age range of 4 and 8 years and compare with age matched typical children. A total of 80 participants were recruited for the study. The clinical group consisted of 30 children with congenital hearing loss and were fitted CI before the age of 3 years. The participants of the clinical group were further divided into two subgroups based on the number of years of cochlear implant use. Subgroup I consisted of participants with 2-3 years of cochlear implant experience and subgroup II with 3-4 years of implant experience. The chronological age of participants in subgroup I was in the range of 4.0-5.11 years (2-3 years of CI experience) and subgroup II in the chronological age range of 6-7.11 years (3-4 years of CI experience). TDC group was also divided into two subgroups of 25 participants each based on the chronological age (4.0-5.11 & 6-7.11 years).of the participants.

The study consists of two major sections: 1. Acoustic analysis 2. Articulatory analysis. The test stimuli for acoustic analysis were simple picturable words and picture stimulus for Malayalam Diagnostic Articulation Test-Revised (MAT-R) was administered for articulatory analysis. Speech samples were elicited through picture-naming task and was audio recorded. The acoustic parameters considered for the study included nine temporal and four spectral parameters. For detailed articulatory profiling, vowels, consonants, and consonant clusters were analyzed quantitatively and qualitatively.

The results indicated significant effect of duration of CI use in both acoustic and articulatory measures. There was no significant effect of gender in any of the parameters investigated. Most of the variables in spectral measures approached normal limits with 2-3 years of CI experience. However, temporal measures were significantly deviant from age matched peers. Interestingly, fricatives and affricates which are generally late acquiring, approached typical values in duration measures with 3-4 years of CI experience. A considerable improvement in the articulatory abilities was also noted for vowels, consonants and consonant clusters with increased duration of CI use. However, children using CI exhibited significantly lower scores for all places and manners of articulation compared to TDC. Although there was a delay in acquisition of articulatory abilities, children using CI exhibited similar trend to that of TDC. The study highlights the importance of intense articulation training for a longer duration following CI surgery to achieve intelligible speech and the need for school/ district wise availability of speech therapy.

Key words: Children using Cochlear Implant, Malayalam, Speech Acoustics, Articulation

Chapter 1: Introduction

Speech, the supreme mechanism possessed by humans is a unique, dynamic, and complex motor activity through which they express emotions and thoughts. It involves different subsystems including respiratory, phonatory, resonatory, articulatory, and the nervous system which interact and coordinate with each other in real time during the production of speech. Speech acquisition is a complex process involving child's mental representation of a language's sound system (phonological development), production of individual speech sounds (phonemes), and the ability to sequence movement of the articulators (tongue, lips, teeth, jaw, and palate) for speech production. It requires many years of refinement for the child to have intelligible adult like productions of vowels, syllable structures, consonants, and prosody. The transformation from babbling to meaningful speech is an important milestone in the development of phonetic and phonological skills in children.

Hearing is the most important sensory modality through which speech and language typically develop. Auditory feedback is critical for the control of respiratory, phonatory, and articulatory functions during speech (Hocevar-Boltezar et al., 2005; Waldstein, 1990). A theory of "internal model" helps in addressing the role of auditory feedback in the production of speech (Perkell et al., 1997; Perkell et al., 2000). According to this theory, a map between vocal tract configuration and its acoustic output exist as a reference for the production of each speech sound. This map is learned with the help of auditory, somatosensory, and visual feedback that is attained during childhood and this feedback is used for calibrating the map in later stages. Thus, children with prelingual hearing loss have less auditory experience in shaping their internal model, and this absence of auditory feedback may lead to a loss of calibration of the suprasegmental and segmental properties of speech and consequently lead to deviance in speech. Thus, deprived auditory feedback to acoustic-phonetic cues can result in poor speech perception and production in children with hearing loss.

According to the 2018 estimates of WHO, 466 million people (>6.1% of the world's population) in the world have disabling hearing loss[1] out of which 93% (432 million) of them were adults, and 7% (34 million) were children younger than 15 years. The prevalence of disabling hearing loss in children is the highest in south Asia region (12.2 million). The prevalence and incidence of hearing impairment in India are also substantially high. Among the disabled population in India, 63 million people (6.3%) suffer from significant hearing loss (Varshney, 2016).The estimated prevalence of childhood-onset deafness in India was found to be 2% (Garg et al., 2009).The National Sample Survey (NSS) 58th round (2002) surveyed disability in Indian households and found that hearing disability was the second most common cause of disability and topmost cause of the sensory deficit. According to the last census of India (2011), the total disabled population in India was 2.21%, out of which hearing impairment accounted for 19% of the disabled population. In India, 20% of the total disabled population having hearing impairment belonged to the age group of 0-19 years while 23% belonged to children in the age group of 0-6 years.

1.1. Speech characteristics of children with Hearing Impairment

Children with bilateral, severe-profound hearing loss appear to have errors at

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[1] Disabling hearing loss refers to hearing loss greater than 40 dB in the better hearing ear in adults (15 years or older) and greater than 30 dB in the better hearing ear in children (0 to 14 years).

both segmental and suprasegmental level compared to typically developing children (TDC). Errors of both vowels and consonants are observed at the segmental level (Levitt & Stromberg, 1983; Paterson, 1994). Most common occurring abnormalities at segmental level include vowel centralization, vowel prolongation, diphthong errors, and nasalization. Errors in consonant production include omission, substitution, and distortion (Tye-Murray & Clark, 1998). Acoustic studies on children with HI have found reduced Voice Onset Time (VOT) (Gilbert & Campbell, 1978; Shukla, 1989) and difficulties in distinction between voiced and unvoiced stops (Ryalls et al., 2003; Samar et al., 1989). Abnormal vowel formants (Angelocci et al., 1964; Nataraja et al., 1998; Paul & Nataraj, 1998; Vasantha, 1995), prolongations of vowels (Calvert, 1961; Shukla, 1987) and smaller bandwidth (Grover & Nataraja, 1998) are also reported.

Early rehabilitation by providing appropriate amplification devices is very crucial in children with HI in terms of speech and language development. Amplification devices basically function by amplifying the sound or increasing the loudness of the sound that reaches the ear of the user. In the past analog hearing aids was the only rehabilitation option available for children with HI. However, with technological advancements, digital hearing aids came into use which has the advantage of better signal processing. However, some children with severe to profound hearing loss do not receive adequate benefit from conventional hearing aids because they fail to provide enough amplification to make sound audible and facilitate speech perception. In this case, cochlear implantation would be the next best option. Cochlear implants have proven to be the pioneer in extending near-normal hearing. The major advantage of a cochlear implant is the amplification of sounds with better restoration of cues for intensity, timing and frequency resolution of the cochlea (Gillis, 2017).

1.2. Cochlear Implant

With the availability of recent technologies and surgical advancements, along with the implementation of universal newborn hearing screening (UNHS), the speech and language outcomes in children with prelingual hearing loss have shown a significant difference (Ertmer et al., 2012; Fulche et al., 2012; May-Mederake, 2012). Restoration of audition through a Cochlear Implant (CI) is manifested to have significant benefit in individuals with hearing loss. A cochlear implant is an electronic device that converts mechanical acoustic energy into electrical energy that stimulates auditory nerves directly, bypassing the damaged or missing hair cells of the cochlea. Cochlear implantation has become a standard procedure in the rehabilitation of children with prelingual hearing loss (Baudonck et al., 2010). Perception of speech could depend on certain cochlear implant factors and subject variables. Studies on cochlear implantees have concluded that the number of channels, the speech coding strategies, and the number of active electrodes are few of the important implant variables that could affect speech perception (Geers et al., 2003). The subject variables would include the age of onset of hearing loss, degree of hearing loss, duration of auditory deprivation before implantation, age of implantation, duration of implant use, duration of listening and speech therapy, and mode of communication used (oral/simultaneous/sign).

1.2.1 Speech characteristics of children using Cochlear Implants

Several studies investigating the speech and language outcomes in children with prelingual hearing loss has reported an overall advancement in their performance post cochlear implantation (Colletti et al., 2012; Shah et al., 2013; Tobey et al., 2011). Better speech perception and production abilities are also reported by researchers (Tobey et al., 1994; Osberger et al., 1991). Reduction in articulatory errors like omission, distortion, and substitutions of consonants appear post-implantation (Geers & Tobey, 1992). Moreover, CI users tend to expand their phonetic repertories and increase the variety of consonant features and eventually improve conversational speech intelligibility (Osberger et al., 1993; Flipsen, 2008).

The advantages of cochlear implants over those using other sensory aids like conventional hearing aids in speech production abilities are well reported (Ertmer et al., 1997; Tobey et al., 1994; Van Lierde et al., 2005). Moreover, children using CIs demonstrate superior speech perception and language skills than children using hearing aids (Miyamoto et al., 1997; Tomblin et al., 1999).

Another important finding of the previous research is that the speech characteristics of children using CI are comparable to that of typically developing children. Research on the acoustic characteristics of speech in children using CI revealed that duration of words (Tye-Murray et al., 1996) and formant frequencies (Fourakis et al., 1993; Seifert et al., 2002) tend to move towards normal values post-implantation. Studies have shown that VOT values of CI users are comparable to that of TDC (Anusha et al., 2010; Kant et al., 2012; Uchanski & Geers 2003).

1.3 Assessment of speech production in children with Hearing Impairment

A detailed evaluation of the speech production abilities in children with HI is inevitable. Speech production skills are assessed in a variety of ways using various speech elicitation tasks which are broadly categorized as imitation, picture naming, and spontaneous speech (Tobey et al., 1994; Tye-Murray & Kirk, 1993). Both subjective and objective methods are adapted for the assessment of their speech characteristics. There are potential advantages and disadvantages to each method of assessment. One of the objective methods of assessing speech production is spectrography, which is a prime technique for making acoustic measurements of speech production. A spectrogram is a visual representation of sound. The speech spectrogram provides detailed quantitative information regarding speech waveform, including the intensity, frequency, duration and spectral analysis (Kent, 1992). One of the freeware that helps in spectrographic evaluation is Praat. Notably, Praat is a user-friendly software that helps the clinician to place reliance on objective scientific data (Boersma & Weenik, 2010).

Subjectively, speech production abilities are commonly assessed using standardized articulation tests and rating scales. Articulation skills can be assessed using screening tests, diagnostic tests, or deep tests of articulation. Articulation tests are language specific as the phonological system varies across languages. Extensive standardized articulation tests have been developed based on the articulatory acquisition in the Indian context as well (Prathima & Sreedevi, 2009; Sridevi, 1976; Tasneem, 1977; in Kannada; Thirumalai, 1972; Usha, 1986 in Tamil; Padmaja, 1988 in Telugu; Divya & Sreedevi, 2010; Maya & Savithri, 1990; Neenu et al., 2011 in Malayalam).Combining both subjective and objective measures would help in better understanding of a child’s speech production abilities. This will further help Speech Language Pathologists in prioritizing and setting up goals during intervention.

1.4 Need for the study

It is established that the speech characteristics of children who have undergone cochlear implantation widely differ from children fitted with digital hearing aids. This difference is mostly owing to the better speech perception using cochlear implants leading to improved speech production. Studies on speech characteristics of children using CI and hearing aids alone are abundant in the literature. From the literature it has been noted that such investigations have been primarily carried out in English, Japanese, Mandarin and to some extent in French, Spanish, Portuguese, and Croatian-speaking children with CI. Since the phonetic or phonological characteristics across languages, it is essential to replicate such studies into other common spoken languages to be able to provide language specific data for rehabilitation professionals working with children using CI.

Studies have reported that temporal parameters are more affected than spectral parameters in children using CI. Majority of available research has focused mainly on the spectral analysis of speech. Other than VOT, temporal aspects of speech production have received scant attention in children using CI and even in TDC. This has to be addressed as timing may be the most critical factor in skilled motor performance like speech (Kent, 1976). Further, there are no published Indian studies which provide detailed profiling of articulatory abilities in children using CI. Articulatory profiling helps SLPs to understand the most affected class of phonemes and further in setting up goals for improving speech intelligibility.

India being a multilingual country has over 22 spoken languages across its stretch. All of these languages belong to a major family of languages such as Indo-Aryan, Dravidian languages, Austro-Asiatic languages, and Tibeto-Burman linguistic languages[2]. Malayalam has a unique phonological system as indicated by the acoustic studies. When compared to other Indian languages such as Hindi and Kannada, Malayalam has a three-way voicing contrast for stop consonants (voiced unaspirated, unvoiced unaspirated, unvoiced aspirated) while the earlier two have a four- way

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[2] Malayalam is one among the Dravidian languages spoken by approximately 38 million people in the state of Kerala, and union territories of Lakshadweep and Puducherry. It has 11 monophthongs, and two diphthongs and 52 consonant phonemes. It consists of 9 places of articulation which are bilabial, labiodental, dental, alveolar, alveolo-palatal, retroflex, palatal, velar and glottal and eight manners of articulation which include plosives, nasals, trills, flaps, fricatives, affricates, central approximant and lateral approximant (Haowen Jian, 2010).

contrast (voiced aspirated, voiced unaspirated, unvoiced aspirated and unvoiced unaspirated). In terms of syllable structures, Malayalam and Hindi have an occurrence of open and closed syllabic structures. Kannada has only open syllables. Regarding the phonological system, Malayalam has more number of phonemes, extra consonants (alveolars, nasals and laterals) and wide varieties of retroflexes and nasal articulators.

Savithri (1989) highlighted the dire need to study and analyze the acoustic characteristics of speech sounds of Indian languages to understand the production and perception of the speech sounds in their culture. This need gets extended with highly limited original published researches investigating the acoustic and articulatory characteristics of Malayalam speaking children with CI. Understanding the acoustic and the articulatory speech features will prove beneficial for post-implantation speech therapeutic services provided to children who are native Malayalam speakers. In the context of recent government policies and schemes in India towards making CI more affordable, economical and accessible for the common man, an increase in the number of children with hearing impairment undergoing CI surgery is on the rise. This is significantly distinct in the state of Kerala as compared to other states in the country due to a highly well-executed CI scheme, ‘Shrutitharangam’, by the state government of Kerala.

‘Shruthitharangam’ is a Kerala government scheme implemented in the year 2012 with the objectives to provide cochlear implant to children with hearing loss less than 5 years of age and to provide financial support for Auditory Verbal Habilitation (AVH) to implanted children through empanelled hospitals/centers. Auditory verbal rehabilitation is provided free of cost for the first two years post implantation. Thus, with an increase in the number of children with CI speaking Malayalam, their effective speech rehabilitation plan should be on strong foundations of language appropriate evidence-based research. This again points out the importance of investigating the acoustics and articulatory characteristics in Malayalam speaking children with cochlear implants in comparison to typically developing children. Moreover, the significance in studying acoustic and articulatory characteristics in combination will help speech language pathologists in identifying subtle deficits affecting the speech naturalness in children with CI.

1.5 Aim of the study

To investigate the acoustic and articulatory characteristics of Malayalam speaking children using cochlear implant and to compare the same with typically developing children in the age range of 4 to 8 years.

1.6 Objectives

The objectives of the study were

1. To investigate the acoustic (temporal & spectral) characteristics of speech across age groups (4.0-5.11 years & 6-7.11 years) in children using cochlear implant and in typically developing children.
2. To compare the acoustic (temporal & spectral) characteristics of speech between children using cochlear implant and typically developing children.
3. To investigate the articulatory characteristics of speech across age groups (4.0-5.11 years & 6-7.11 years) in children using cochlear implant.
4. To compare the articulatory characteristics of speech between children using cochlear implant and typically developing children.

1.7. Hypotheses

The null hypotheses framed for the present study were

1. There is no significant difference in the acoustic (temporal & spectral) characteristics of speech across age groups (4.0-5.11 years & 6-7.11 years) in children using cochlear implant and in typically developing children.
2. There is no significant difference in the acoustic (temporal & spectral) characteristics of speech between children using cochlear implant and typically developing children.
3. There is no significant difference in the articulatory characteristics of speech across age groups (4.0-5.11 years & 6-7.11 years) in children using cochlear implant.
4. There is no significant difference in the articulatory characteristics of speech between children using cochlear implant and typically developing children.

Chapter 2: Review of Literature

Speech is a system of verbal communication that is distinct to human beings. Speech is a learnt behavior which begins from birth and continues to develop till puberty. During this period, complex interactions are established between language and the motor centers in brain. The maturation of these complex connections leads to changes in the early non-speech sound production into a more controlled purposeful speech at the articulatory level. Like any other skilled movement, the production of speech requires coordination of several subsystems like the respiratory, phonatory and different parts of the vocal tract. Integration of auditory, somatosensory, and motor information is a prerequisite for the accurate production of speech. Hearing is the most important sensory modality through which speech and language are typically developed (Ross & Giolas, 1978). Auditory input plays a vital role in the development of speech motor control (Perkell et al., 1997). It is through continuous auditory stimulation of speech and other sounds in the environment that a child can acquire language (Whetnall & Fry, 1964).

2.1. Importance of Auditory Feedback in Speech Production

Models of speech production consider that the production of speech is controlled majorly by two mechanisms: A feedback-based loop and a feed-forward control system. In the feedback-based loop system, the central nervous system (CNS) generates an efferent signal, corresponding to the estimated auditory (or somatosensory) consequence of the articulatory movements. This efferent signal is then compared to the actual auditory (or somatosensory) feedback signal produced by the speaker (reafferent sensory input). When a discrepancy happens, an error signal is generated, and the motor system modifies or minimizes the discrepancy between the expected and actual auditory or somatosensory feedback. On the other hand, the feed-forward control system involves commands that are executed without regard to feedback and are stored in memory. During childhood, it is considered that speech sounds are mainly produced through feedback system. A typical auditory feedback system is essential for controlling and monitoring aspects of speech, including voice, articulation, and fluency (Webb & Adler, 2008). As the child gets older, feed-forward commands are stored and feedback becomes less necessary for the online control of speech movements (as demonstrated by the fact that adults who become deaf may remain intelligible for years before their speech degrades) (Guenther et al., 2006; Perkel et al., 2000).

Hearing impairment (HI) is a significant global health issue due to its growing prevalence and negative impact on the quality of life. It reduces the number of listening experiences that the child has and thus slows down the process of speech and language development resulting in impairment in articulation, phonology, voice, resonation, prosody, and fluency characteristics. In children with severe to profound hearing loss, the speech motor control system is forced to rely on feed-forward commands, which slowly degrade with time. The extent of the effect of this deprivation depends on the onset of hearing loss. The magnitude of the problem will be higher if it is a prelingual hearing loss.

2.2. Speech Characteristics of Children with Hearing Impairment

The speech of children with HI is characterized by limited fluency and inappropriate pauses during speech. Slow and labored speech is another characteristic of children with severe to profound degrees of HI. They exhibit limited variations in pitch and thus resulting in monotonous stress pattern and excessive stress on all syllables throughout the utterance (Hargrove, 1997; Stathopoulos et al., 1986).

2.2.1. Acoustic Characteristics of Children with Hearing Impairment

Vowel production errors are common in the speech of children with profound hearing loss. Many of the errors can be attributed to inaccurate tongue placement and posture resulting in abnormal formant frequencies (F_1/ F_2) (Angelocci et al., 1964; Nataraja et al., 1998; Vasantha, 1995). The formant frequencies show reduced ranges during the production of different vowel qualities and there can be extensive overlap of vowel areas that can result in reduced or centralized vowel space area (Angelocci et al., 1964; Nicolaidis & Sfakiannaki, 2007; Sapir et al., 2010; Smith, 1975). The reduced vowel space can result in reduced intelligibility of speech of these children with HI compared to TDC (Horga & Liker, 2006; Ozbic & Kogovsek, 2010; Shukla, 1989). Generally, more errors have been reported for high and mid vowels compared to low vowels and for front than back vowels. Further, a higher fundamental frequency (F_0), jitter, and shimmer are also reported (Angelocci et al., 1964).

The temporal characteristics of the speech of children with HI are also affected. Typically longer vowel durations have been reported in several studies (Anusha et al., 2010; Calvert, 1961; Nicolaidis & Sfakiannaki, 2007; Shukla, 1987; Whitehead & Jones, 1978). As reported by Parkhurst and Levitt (1978), speech of individuals with HI is 1.5 to 2 times longer than those of normal hearing speakers. This could be due to the insertion of pauses and excessive prolongation of speech segments (Boone, 1966). The prosodic aspects like control over stress and intonation are affected in children with hearing loss. Errors in voicing distinction are one of the common errors seen in these children. Reduced VOT (Anusha et al., 2010; Gilbert &

Campbell, 1978; Shukla, 1989), difficulty in voiced-unvoiced distinction (Calvert, 1961; Monsen, 1976; Samar et al., 1989) are commonly reported in literature. The tendency of production of smaller than normal VOT differences could be attributed to the difficulty in coordinating oral and laryngeal gestures (Brown & Goldberg, 1990; Monsen, 1976). The production of other classes of sounds like fricatives and affricates are also reported to be affected in children with HI.

2.2.2. Articulatory Characteristics of Children with Hearing Impairment

The overall intelligibility of speech generally reduces, particularly as the linguistic complexity increases (Radziewicz & Antonellis, 1997).The articulatory errors seen are described as similar to those of young typically developing children. The most common articulatory errors involve consonants (fricatives, affricates, liquids, semivowels, plosives, and errors with consonant blends) and to an extent, nasals (Abraham, 1989). Consonant productions are generally characterized by omissions and distortions. Vowel productions are generally accurate and usually the productions of front-mid or high vowels are affected than back low back vowels (Boone, 1966; Eisenberg, 2007; Smith, 1975). Difficulties in phonation, respiration, speech rate, resonance, voice quality, consonant and vowel productions, suprasegmentals, and coarticulatory movements are widely reported (Ling, 2002). The phonological processes seen in children with HI are found to be similar to typically developing children but with increased frequency. According to Flipsen and Parker (2008), devoicing of stops, cluster reduction, final consonant deletion, fronting, liquid simplification, gliding, and stopping are the most common developmental processes seen in children with HI.

As observed from various studies it is evident that prelingual HI can adversely affect the speech production in children. Impaired perception of speech results in deterioration of speech intelligibility, voice quality and prosody. Early identification and rehabilitation can significantly reduce the negative impact of HI on speech production and thus quality of life.

2.3. Early Detection and Management of Hearing Impairment

Early auditory experience is crucial for the development of speech and language skills (Oller, 2000). Longer the brain is deprived of auditory input, greater the resulting sensory deprivation. For this reason any impairment in hearing needs to be identified as early as possible (Yoshinago-Itano, 2004). For instance in India, the primary goals of the early detection and intervention program under Universal Newborn Hearing Screening (NHS) program is mentioned as “1-3-6” goals. This indicates that every newborn may be screened before one month of age, diagnose hearing loss and fit with hearing aid before three months, and admit the child for early intervention before six months of age (Patel & Feldman, 2011). This protocol is extensively accepted and has been institutionalized as a standard of care by hospitals nationwide. NPPCD (National Program for Prevention and Control of deafness) and RBSK (Rashtriya Bal Swasthya Karyakram) are other significant milestones in the systematic implementation of hearing screening programs in India. Early Hearing Detection and Intervention (EHDI) programs targets setting a new target of 1-2-3 month goal (screening by one month of age, audiologic diagnosis by two months of age, and intervention initiated no later than three months of age). The most recent and widely followed protocol by Joint Committee on Infant Hearing (JCIH) also follows a 1-2-3 month timeline.

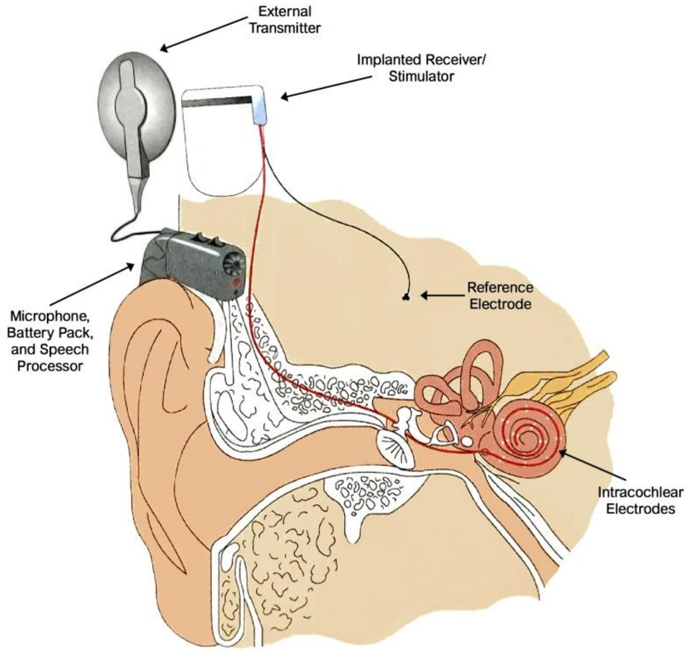
Early auditory rehabilitation is very crucial in children with HI. To shorten the duration of auditory deprivation caused by HI, hearing aids or cochlear implants are the best rehabilitative option to provide improved biofeedback. Few children with severe to profound HI do not receive adequate benefit from the conventional digital hearing aids because they fail to provide enough amplification to make sounds audible and facilitate speech perception. In this case, cochlear implantation would be the next best option. The major advantage of a cochlear implant is the amplification of sounds with better restoration of auditory cues for intensity, timing and frequency resolution of the cochlea (Gillis, 2017). These cues may be critical for the user to monitor his or her speech and to make purposeful moment-to-moment adjustments in voicing.

2.4. Cochlear Implant (CI)

In normal hearing, sound travels through the outer ear, middle ear, inner ear, and auditory nerve to the brain after undergoing a series of transformations. The hair cells of the basilar membrane convert mechanical information into neural signals. In individuals with sensorineural hearing loss (SNHL), these hair cells are degenerated or are absent, that result in the blockage of sound transmission to the brain. A cochlear implant (CI) electrically stimulates the remaining auditory neurons bypassing normal hearing mechanisms. Electrodes are surgically implanted in the cochlea in the location of the damaged hair cells. A CI consists of both internal and external components as shown in Figure 2.1. The external components include a microphone, a signal processor, and a transmitter. The microphone captures acoustic signals, transduces them into an analog electrical signal that is sent to the processor. The processor modifies the signal and sends this to an external transmitter that is placed on the skin (radiofrequency transmission), to a subcutaneous receiver embedded in the mastoid bone beneath the transmitter. Figure 2.2 depicts the schematic representation of a cochlear implant.

Figure 2.1

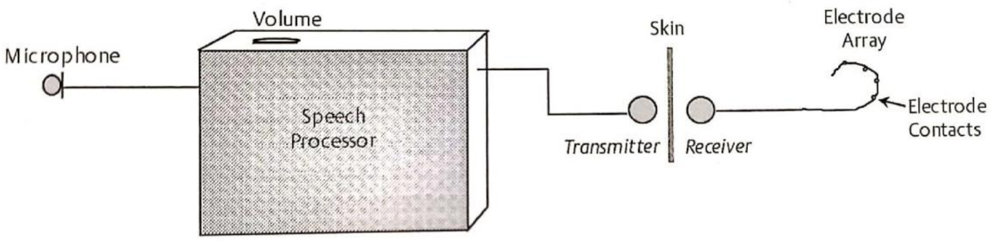
External and Internal Components of a Cochlear Implant



Note. From: Young, N. M., & Kirk, K. I. (Eds.). (2016). *Pediatric cochlear implantation: Learning and the brain*. Springer

Figure 2.2

Schematic Representation of Cochlear Implant



Note. From: Waltzman, S. B., & Roland, J. T. (2014). *Cochlear Implants.* Thieme

An array of electrodes extending from the receiver is inserted into the cochlea. These electrodes receive electrical stimulation that stimulates the cochlear neurons of the auditory nerve (bypassing the damaged hair cells), and produces a sensation of sound. The temporal information of the speech signal is commonly divided into envelope (2–50 Hz) which is the slow variations in the speech signal, periodicity (50–500 Hz) which conveys F_0 information, and temporal fine structure (TFS; 500–10,000 Hz) that helps in pitch perception, sound localization and binaural segregation of sound sources (Rødvik et al., 2019).

The characteristics of CIs vary with respect to the manufacturer of the product. Four major manufacturers of CI include Advanced Bionics Corporation (American), Cochlear Ltd, Cochlear Corporation (Australian), MedEl Corporation (Austrian) and Neurelec (France). Among these, most commonly available manufactures are Advanced Bionics, Cochlear and MedEl (ASHA, 2004). Table 2.1 shows the summary of the characteristics of CI provided by various manufacturers. All three of these devices make use of (1) multichannel stimulation (multiple electrodes in the array), (2) transcutaneous (through the skin) transmission (3) telemetry (for monitoring the intracochlear electrodes), (4) a choice of different speech processing options, and (5) programming which involves establishing a threshold and maximum stimulation level for each of the electrodes. All three types of implants are similar in cost.

Table 2.1

Summary of Characteristics of CI Provided by Various Manufacturers

CI features	Advanced Bionics	Cochlear	MedEl
No. of electrodes	16	22	24
No. of channels	16	22	12
Speech processing strategies	CIS,MPS, HiRes Fidelity 120TM,ClearVoice TM, Optima Sound processing	Hi –Ace (CI24RE, CI422) Ace(N24,CI500) SPEAK(N22, N24)	FSP, HICIS

Note. CIS-Continuous Interleaved Sampling, MPS- Multiple Pulsatile Sampler, HiRes fidelity-High Resolution fidelity, ACE-Advanced Combination Encoder, SPEAK-Spectral Peak, FSP- Fine structure processing, HICIS- High Definition Continuous Interleaved Sampling.

2.4.1. Candidacy Criteria

The current candidacy criteria for pediatric cochlear implantation (Larson, 2020) include:

1. Bilateral profound hearing loss (unaided thresholds ≥ 90 dB)
2. Delay in developmentally appropriate auditory skills and milestones
3. Minimal benefit from hearing aids (defined as <20-30% on single-syllable word tests)
4. No indications of central auditory lesions, including auditory nerve aplasia
5. No medical contraindications for surgery in general

Absolute contra-indications for cochlear implantation include cochlear agenesis, complete obliteration of the eighth nerve and substantial progress with the use of hearing aids. As cochlear implant devices continue to improve, the criteria regarding the degree of hearing loss will also continue to evolve. However, all the sounds that can be detected and conveyed by a normal cochlea (16,000 hair cells) cannot be entirely replaced by a processor. The sound signal received by a cochlear implant need not be exceptionally clear even with a high-functioning implant. Children who have undergone a CI surgery have to be systematically trained to interpret this electronic signal. There lies the importance of intensive Auditory Verbal therapy (AVT) and speech therapy post cochlear implantation. Many rehabilitation centers recommend 3-6 months of hearing aid use before implantation, enrollment in auditory verbal rehabilitation programs, realistic expectations and willingness of the family.

2.4.2. Variables Affecting Speech Perception through CI

The progress of every child in terms of speech perception and production depends on various aspects. Numerous investigations have attempted to identify the factors that influence the outcomes in children using CI. The factors that are most frequently reported as having a significant impact on speech acquisition and development in children using CI are discussed here. This includes both subject and implant related variables that could affect the performance of children using CI.

2.4.2.1. Subject Related Factors.

1. Etiology of Hearing Loss: The role of etiology in the speech production abilities of children with HI is varied. Studies have indicated that etiology of hearing loss might not play a crucial role in speech production skills post-implantation (Sarant et al., 2001; Tobey et al., 2003). However, when etiology was found to be a significant predictor of outcome, it was often associated with other comorbid conditions and negatively affected performance (Bauer et al., 2003). Disabilities that were considered to affect postoperative outcome included mental retardation, autism, cerebral palsy, and a variety of genetic syndromes (Lesinski et al., 1995).

2. Age of Onset of HI: Those children who had an early onset of hearing loss and had a longer duration of profound loss demonstrated poorer speech perception abilities (Mecklenburg, 1988; Osberger et al., 1991) and thus affecting the speech and language development. Children with post lingual hearing loss exhibited a marked trend towards better speech and language development (Geers et al., 2003; Osberger et al., 1991; Sarant et al., 2001).

3. Age of Identification of Hearing Loss: The age at which the child's HI is diagnosed, and when the child is provided with hearing aids, may represent a good marker for the initiation of family training and attention to the hearing loss (Geers & Brenner, 2003; Swami et al., 2013; Yoshinaga-Itano, 2003). The results of study by Yoshinaga-Itano (2000) demonstrated the importance of identification before six months of age for subsequent oral language development.

4. Pre-implant Residual Hearing: Regardless of age, research has shown that individuals who have greater preoperative residual hearing tend to have better outcomes (Dettman et al., 2004; Dowell et al., 2004; Eisenberg et al., 2000; Gupta, 2012; Niparko et al., 2010; Sehgal et al., 1998). There may be a more 'intact' auditory system in these children, which provides an adequate neural substrate for the electrically induced excitation patterns (El-Hakim et al., 2002).

5. Degree and Duration of Auditory Deprivation prior to Implantation: Increase in the degree and duration of HI prior to cochlear implantation would negatively affect speech perception (Dowell et al., 1995) and production abilities. This is because of the sensory deprivation that happens in the absence of auditory stimulation which results in failure of the neural structures to mature (Shepherd et al., 1997).

6. Age of Implantation: Various authors have reported that speech production abilities were better in children who were implanted earlier compared to late implanted children (Connor et al., 2006; Gaurav et al., 2020; Gupta, 2012; Kirk et al., 2002; Mao & Xu, 2017; Seifer et al., 2002; Sharma et al., 2020; Svirsky et al., 2004). Significant improvements in the production of consonants (Kirk et al., 1995) and vowels (Ertmer et al., 1997) post-implantation are established. It was also found that children who were implanted before the age of 2 years showed significantly greater language development than those who were implanted later (Boons et al., 2012). The speech perception and linguistic skills in children who were implanted by the age of 4 years were found to be better than children implanted later (Shakrawal et al., 2020).

More rapid learning curves are reported in children implanted at a younger age than older age implantees even after six years of follow up. Further, studies have reported that children who were implanted earlier performed similar to that of normal-hearing peers (Kameswaran et al., 2006; Shakrawal et al., 2020). Researchers suggest that the impact of age at implantation is related to the developmental plasticity of the central auditory system (Gordon et al., 2003; Sharma, 2002; Sharma et al., 2002; Shephard et al., 1997). Neurological changes occur in the brain as a result of auditory deprivation, which results in functional reorganization of central auditory structures in response to sensory input via a cochlear implant (Shephard et al., 1997).

7. Duration of Implant Use: Duration of CI use is quoted as one of the predominant factors determining the success of implantation (Blamey et al., 2001; Boonen et al., 2020; Easwar et al., 2016; Mao & Xu, 2017; Shakrawal et al., 2020). A steady improvement in the accuracy of word and phoneme production has been observed with increase in the duration of implant use (Bouchard & Normand, 2007;

Sevinc et al., 2009; Shakrawal et al., 2020). The speech perception and intelligibility improved significantly even after five years of implant use (Miyamoto et al., 1996). Studies have reported a general slowness in phonetic inventory development after six years of implant experience; which becomes almost steady by the age of 8 years of CI use indicating the maturation of the central nervous system. As the nervous system matures, it loses some of its plasticity. These findings support the theories of critical periods in the development of spoken language (Blamey et al., 2001).

8. Hours of CI use per Day: A strong positive relationship between daily device use and communication performance in children using CI has been reported (Gagnon et al., 2020; Wie et al., 2007). Literature suggests the usage of CI 8–9 hours a day as a metric of full-time use (FTU) in children and lesser wear time resulted in poorer outcomes (Contrera et al., 2014; Easwar et al., 2016; Wiseman & Warner-Czyz, 2018). Consistent stimulation ensured by full-time long term use of CI promotes the strengthening of synapses which facilitates auditory capabilities of the implanted ear.

9. Intensive Auditory Verbal Rehabilitation: Children who receive intensive auditory stimulation exhibits significant improvements in language acquisition, literacy development, speech perception and speech production (Dowell et al., 2002; Mildner et al., 2003; Papsin et al., 2000; Svirsky, 2000; Szagun, 2001). After six months of implant use, acquisition of new sounds has been reported (Ertmer & Goffman, 2011; Sabri & Fabiano-Smith, 2015). At least 12 months of audio-verbal rehabilitation and speech and language therapy are required to compare the effects of cochlear implant in any set of children (Shakrawal et al., 2020).

10. Communication Mode: The mode of communication, oral/ sign/ simultaneous, used post implantation influences speech development (Kirk et al., 2002; Schauwers et al., 2004). Children who were using an oral mode of communication had better outcomes (Bouchard et al., 2007; Moog & Geers 2003; Spencer, 2004). Children who used sign systems before receiving a CI kept relying on them for at least two years after surgery, whereas, oral communication users focused predominantly on oral articulation only (Tye-Murray et al., 1995).

11. Parental Involvement/Motivation: The parents' involvement in child's auditory verbal rehabilitation has been cited as essential to post-implant linguistic performance (Easterbrooks et al., 2000; Geers & Brenner, 2003). Spencer (2004) found that personal parental involvement in the process of deciding upon cochlear implantation and the subsequent educational rehabilitation was positively correlated with linguistic development in implanted children.

2.4.2.2. Implant Related Factors.

Most of the studies on cochlear implantees have indicated that the number of channels, the speech coding strategies, and the number of active electrodes are the important variables that could affect speech perception.

1. Number of Channels: This can be of two types-single channel and multiple channel cochlear implants. A single-channel cochlear implant electrically stimulates a site in the cochlea using a single electrode, whereas, multi-channel implants stimulate multiple sites in the cochlea using multiple or an array of electrodes. Depending on the frequency of the incoming signal, different sites of the electrode array are stimulated.

2. Speech Processing Strategies: A speech processor filters the acoustic information collected from the microphone and converts them into a coded signal. This can be compared with the function of cochlea and higher centers of the brain. The method of deriving the signal sent to the implant is called the Coding strategy (Moore, 1985). Widely used coding strategies are filter bank and feature extraction procedure. In the filter bank procedure, the signal is separated into frequency bands which are transmitted as an analog input. In the feature extraction procedure, the signal which provides the highest degree of speech recognition is focused. Different speech processors use different speech strategies. The speech processor strategies available in cochlear implants typically are of 3 categories (Moore & Teagle, 2002). F0/F1/F2, multipeak (MPEAK), and spectral peak (SPEAK) strategies emphasize the frequency components of speech while compressed analog (CA), simultaneous analog sampler (SAS), and continuous interleaved sampling (CIS) strategies emphasize the temporal or timing characteristics of speech. There are also hybrid strategies, which combine both frequency and temporal emphasis, including advanced combination encoder (ACE) and n of m (n = number of electrode sites available for stimulation for a given speech input, m = total number of sites).

3. Number of Active Electrodes: The speech perception can also depend on the number of active electrodes in the child's CI map. Literature review on the effect of the number of electrodes on speech perception is varied. According to Geers (2003), it is difficult to determine whether the number of electrodes plays a significant role as children using either medium or small number of electrodes in the map is relatively less. Children with a greater number of active electrodes and wide dynamic ranges have higher speech production scores than children with fewer active electrodes (under 10) and narrow dynamic range (Tobey et al., 2003). The optimal performance on speech perception could be achieved if the electrode array consists of 8 to 12 functional channels (Dorman et al., 2000).

Other factors which influence crucial advancements in speech accuracy also include sophistication of the CI technology (Tobey et al., 2000; Tobey & Geers, 1995), contralateral stimulation with a CI or hearing aid, monolingualism, sufficient involvement of the parents, and oral communication by the parents (Boons et al., 2012). Besides all these factors, the developmental path of a child depends mainly on his or her natural ability to learn and make sense of the information he or she extracts from the environment. Recent research into the speech production of children with HI suggests that auditory information received via a CI contributes to improved speech production abilities compared to children using HAs (Anusha et al., 2010; Baudonck et al., 2010; Boonen et al., 2020; Ertmer et al., 1997; Horga & Liker, 2006; Jafari et al., 2017; Kirk et al., 1995; Lopez et al., 2013; Sehgal et al., 1998; Tobey et al., 1994).

With technological advancements and considerable enhancements in speech and language outcomes as supported by various researches, cochlear implantation has gained acceptance worldwide. It is well reported that the performance of children using CI was comparable to that of typically developing children; however, contradicting findings were also documented. Various acoustic, physiological, perceptual and articulatory measures were used to investigate the speech characteristics in children using CI. As the present study aimed to compare the acoustic and articulatory measures in children using CI and typically developing children, the literature review emphasizing these parameters in both the population are dealt in detail in the upcoming sections.

2.5. Speech Characteristics of Speech in Typically Developing Children (TDC)

2.5.1. Acoustic Characteristics of Speech in TDC

2.5.1.1. Vowels.

The literature on vowel development indicates that the acquisition of vowels is early both in terms of perception and production. Most commonly investigated parameters of vowels include fundamental frequency, formant frequency, vowel duration, and vowel space area. A review on studies of vowels in children who babble observed a tendency for front, low and mid-central vowels to be preferred across languages (MacNeilage & Davis, 1990). Among the different vowel acoustic characteristics, vowel duration is studied across languages in TDC. Vowels before voiced consonants are reported to be longer than voiceless consonants (Chen, 1970; Klatt, 1973). Longer duration for low vowels compared to high vowels is reported in Kannada (Savithri, 1986). Other developmental studies have indicated that vowel duration decreases with age and these changes were more evident for short vowels than long vowels (Sreedevi, 2007 in Kannada; Venkat & Lakshmi, 2012 in Oriya). Further, mean F_1 for low-mid vowels (/a/ and /a:/) were the highest than back high vowels (/u/ and /u:/). On the other hand, the mean F_2 values of high vowels (/i/ and /i:/) was the highest and back high vowels (/u/ and /u:/) were found to have the lowest (Krishna, 2009 in Telugu).

The acoustic properties of vowels are influenced by numerous factors such as age, physical status, or gender of the speaker (Huber et al., 1999; Perry et al., 2001). The length of the vocal tract determines the overall patterns of formant frequencies (Whiteside & Hodgson, 2000). The relationship between the first two formants is considered the most important acoustic cue of vowel auditory recognition (Ladefoged & Johnstone, 2010) and the auditory quality of a vowel (Ladefoged & Disner, 2012).

Concerning the relationship between physical changes and speech development, it has been found that as the length of the vocal tract increases during development, formant frequency decreases (Fant, 1960; Fitch & Giedd, 1999), however, this relationship is not linear. Significant differences in formant frequencies occur between three and five years of age though vocal tract length increases from infancy. The formant values are highest in children and lowest in adult males (Deme, 2012; Eguchi & Hirsh, 1969; Huber et al., 1999). Also, variability in formant frequency was noted to be higher for the vowel /a/ compared to /i/ and /u/. Further, F1 is reported to be more robust (Sreedevi & Nataraj, 2000). Other factors which may contribute to the changes in formant frequencies include the opening of lips, placement of tongue, mandible and soft palate (Sundberg, 1969). Various attempts have been made to study formant frequencies in Indian languages like Hindi (Ganesan et al., 1985), Telugu (Krishna, 2009), Kannada (Rajpurohit, 1982; Sreedevi, 2000).

The value of formant frequencies was found to be decreasing with age (Sreedevi, 2000). Extensive research has been done on the fundamental frequency (F_0) characteristics of children at various ages. Most of these studies indicated that prior to puberty; there is no significant difference in the F_0 of boys and girls (Lee et al., 1999; Vorperian et al., 2009). Gender differences in F_0 emerge only by the age of seven and decrease significantly in male children only between the ages of five and ten (Hasek et al., 1980). However, an evident difference in male and female F0 is noted by the age of 12 (Lee et al., 1999). Moreover, between the ages of 4 and 12, formant frequencies differentiate gender, whereas after the age of 12 the F_0 differentiates gender (Perry et al., 2001). Vorperian and Kent (2007) used the composite data F_1 - F_2 plots to characterize major developmental features and reported a decrease in both formant frequencies and vowel space area with age.

2.5.1.2. Stops.

Stops are the most common consonants which occur in all human languages (Ladefoged & Maddieson, 1996) and are produced by the complete occlusion of the cavity by the articulators followed by a release. Among the temporal characteristics of stops, voice onset time (VOT) has been studied across languages in typically developing children (TDC) (Fant, 1980; Lisker & Abrahamson, 1964; Shukla, 1989; Sreedevi, 1990; Savithri, 1996). VOT is defined as the time difference between the onset of articulatory release and the onset of voicing and is considered as a major cue for differentiating prevocalic stops along the voicing dimension (Lisker & Abrahamson, 1964). VOT values differ according to the place of articulation. In English, velar plosives exhibit the longest VOT and bilabials have the shortest (Smith, 1978). In Dravidian languages, velars had the longest VOT which was followed by bilabials and alveolars (Savithri et al., 2001). The duration of VOT is found to be longer for unvoiced plosives compared to voiced plosives in both English and other Dravidian languages like Tamil, Kannada, and Malayalam (Docherty, 1992; Lisker & Abramson, 1964, 1967; Savithri et al., 2001; Shukla, 1989). Also, voiced stops showed lead VOT and voiceless stops lag VOT in Kannada (Savithri, 1996; Savithri et al., 2007; Shukla, 1989).

VOT values were found to be decreasing with age (Menyuk & Klatt, 1975; Smith, 1978; Brinca et al., 2016). Also, high variability in the VOT values was observed in children indicating the refinement in the coordination between vocal fold vibration and articulatory release (Eguchi & Hirsh, 1969; Whiteside et al., 2003). It was also noted that variability in VOT in children decreased with age for both voiced (Whiteside et al., 2003) and unvoiced stops (Brinca et al., 2016; Whiteside et al., 2003). These patterns of decreasing variability with age are suggestive of maturing speech motor skills, while the residual levels of variability could be interpreted as a prerequisite for the organization of motor speech behavior and the development of motor speech schemas. An adult-like VOT has been reported to be achieved by the age of 9-10 years (Lundeborg et al., 2012).

Gender differences in VOT values have been reported by few authors. Whiteside and Marshall (2001) measured VOT patterns of /p, b, t, d/ in 30 children aged 7, 9, and 11 years. They found a marked longer VOT for /p, t, d/ only for boys at age 9 years. The authors concluded that this gender difference might be related to the sudden changes in fundamental frequency in boys around the age of 7–8 years, related to anatomical changes that occur during the onset of puberty. In contrast, a study by Whiteside et al. (2004) found a significantly longer VOT in girls at the age of 13 years. Similarly, a longer VOT for alveolar stops in girls was reported by Swartz (1992). Thus, it is still unclear whether gender differences occur during VOT acquisition in children.

Apart from VOT, few investigations have been carried out on burst duration and closure duration of stops. The burst duration of unvoiced stops is reported to be longer compared to voiced stops (Kent & Read, 2002). Similarly, another acoustic event related to the production of stops is closure duration which is the period of occlusion before articulatory release, which is more salient in word-medial position. Shorter closure duration for voiced stops compared to unvoiced stops has been reported by Savithri (1996) in Kannada. Among the unvoiced stop consonants, closure duration for retroflex was found to be longer, and dental stops were found to be the shortest. Also, among the voiced stop consonants, bilabials exhibit the longest closure duration and retroflex the shortest (Savithri, 1996).

2.5.1.3. Nasals

Nasals are one among the early acquiring sounds and are produced with closure of the oral cavity and radiation of the sound through the nasal cavity while the obstruction is maintained. Acoustically nasal continuants are characterized by nasal murmur, F_1 at around 300 Hz, damped formants, wide bandwidths and formant transitions. On a spectrogram, the boundaries of nasals are determined by the presence of anti-resonances or a lack of energy in frequencies above 1 kHz, along with significant energy at low frequencies. The waveform would exhibit diminished amplitude and a smoother periodic waveform shape relative to the subsequent vowel sound (Uchanski & Geers, 2003). The nasal murmur holds static cues for the perception of place of articulation in nasal consonants (Ohde, 1994).

2.5.1.4. Fricatives and affricates.

Fricatives and affricates are the class of sounds which are late to emerge in normal speech acquisition (Dodd et al., 2003; MacLeod et al., 2011). The acoustic parameters which are of interest for the present study are fricative and affricate duration. The fricative duration serves to discriminate sibilant and non-sibilant fricatives, in which /s/ and /ʃ/ being longer compared to /f/ and /θ/ (Behrens & Blumstein, 1988a; Fox & Nissen, 2005). However, no difference in the duration between /s/ and /ʃ/ was observed and /f/ was found to be longer than /θ/ (Behrens & Blumstein, 1988). Frication duration acts as a significant cue in the syllable initial position for voicing distinction in which unvoiced fricatives having longer noise durations than voiced fricatives. Similar findings were observed for fricatives in both isolated syllables (Baum & Blumstein, 1987; Behrens & Blumstein, 1988) and in connected speech (Crystal & House, 1988). Further, the fricative duration was found to be decreasing with age (Fox & Nissen, 2005; Nissen & Fox, 2005).

2.6. Speech Characteristics of Children using Cochlear Implant

2.6.1. Acoustic Characteristics of Speech in Children using CI

2.6.1.1. Vowels.

Investigations on vowel production in children using CI are quite extensive. The major parameters under study include fundamental frequency (F_0), formant frequencies (F_1, F_2, & F_3), vowel space area (VSA) and vowel duration. Concerning the vowel production characteristics in children using CI, it has been found that cochlear implantation leads to greater differentiation of the vowel inventory (Ertmer, 2001). Pitch control in children using CI was found to be improving with increase in duration of CI use. There was a significant decline in F_0 during the first year after implantation. The values approached normal limits by the end of the second year after implantation (Joy et al., 2017; Wang et al., 2017). The authors describe the first six months after implantation as the auditory adaptation period and sound perception stage. During this period, children with prelingual HI would try to listen and adapt to the sound from the CI. As auditory feedback is habituated, the neuromuscular control of phonation gradually matures.

Subsequently, they will be able to coordinate the movements of vocal folds, reduce the tension of vocal cords, lower their intonation, and gradually stabilize phonation. Similar to this finding, normalization of F_0 within one year of implant use are also well reported (De Souza et al., 2012; Perrin et al., 1995). In contrast to this finding, a higher F_0 of vowels has been reported in children using CI compared to TDC (Coelho et al., 2009; Hamzavi et al., 2000; Higgins et al., 2003; Hocevar-Boltezar et al., 2005; Jafari et al., 2017; Lenden & Flipsen, 2007; Lopez et al., 2013; Van Lierde et al., 2005; Wang et al., 2017). However, few other researchers have reported lower mean F_0 values in CI group (Seifert et al., 2002; Srividya et al., 2016).

No significant difference in F_0 between males and females are also noted (Baudonck et al., 2011; Miljkovic et al., 2014).

A vowel may be described according to the up-down or posterior-anterior displacement of the tongue which correspond to the first formant (F_1) frequency and the second formant (F_2) frequency respectively (Pols et al., 1969). Research in various languages have shown that formant frequencies were within the normal limits in children using CI (Boudonck et al., 2011; Fourakis et al., 1993; Kant et al., 2012; Kunisue et al., 2006; Horga & Liker, 2006; Uchanski & Geers, 2003). However, few studies have observed that the formant frequencies of vowels produced by CI users were higher compared to TDC (Jafari et al., 2016). Also, in cases of vowel confusions, they tend to have a bias towards higher frequencies for at least two years after implantation.

There are few reports of variable findings on formant values. Frequency of the first formant in the CI group was observed to be reduced compared to TDC (Liker et al., 2007; Verhoeven et al., 2016). In contrast, an increase in F_1 was observed for all vowels in CI (Jafari et al., 2016; Jafari & Yadegari et al., 2016; Rohini & Premalatha, 2011; Srividya & Premalatha, 2016). Higher F_1 values could be due to confusions in tongue height. Higher F_3 in the CI group could be due to less degree of constriction of vocal tract. In contrast, a lower F_1 and F_2 for /e/ are also noticed (Kant et al., 2012). F_2 in the CI group was found significantly different from the TDC group for a few vowels. Similarly, higher F_2 has been reported in children with CI (Rohini & Premalatha, 2011). A lower F_2 for front vowels and a higher F_2 for back vowels were observed indicating faulty tongue positioning for back vowels (Anusha et al., 2010; Jafari et al., 2016; Verhoeven et al., 2016). It was also reported that F_2 for /i/ was relatively higher for the CI users compared to other vowels (/a/ and /u/) and this could be due to the fact that /a/ and /u/ have better speech perception in the F_2 region indicated as an advantage of cochlear implantation (Anusha et al., 2010). Also, greater difficulty in the production of mid-vowels than the high or the low ones in children with HI has been established (Liker et al., 2007; Tobey et al., 1996). Another observation on formant values in CI was the significantly larger intra-subject variability in the mean formant values indicating articulatory inconsistency (Boudonck et al., 2011; Verhoeven et al., 2016). It can be understood that the CI group had a less consistent degree of mouth opening and front-back dimension.

The variability in findings concerning formant values is evident from the Vowel Space Area (VSA). The vowel space of children using CI has been described as significantly reduced when compared to TDC (Grandon et al., 2014 in French; Horga & Liker, 2006; Liker et al., 2007 in Croatian; Neumeyer et al., 2010 in German; Reni et al., 2020 in Tamil) indicating deviant articulatory abilities in children using CI. A marginal increase in mean vowel space area (VSA) have also been reported in children with CI (Baudonck et al., 2011) due to a change in F_1 for the /i/ and /u/ vowels (Hocevar-Boltezar et al., 2008). Apart from this, fronting of the vowel space in CI children was also reported (Liker et al., 2007; Kishon-Rabin et al., 2002) which may possibly be explained by the tendency of SLPs, family, and children themselves to move articulation to where it can be more visible, i.e., shift it toward the front of the mouth (Kishon-Rabin et al., 2002). However, VSA in children using CI was reported to be similar to that of TDC (Baudonck et al., 2011; Deepthy & Sreedevi, 2019b; Ertmer, 2001; Uchanski & Geers, 2003).

Another prominent characteristic of the speech of individuals with HI is the tendency to elongate the duration of vowels in their speech (Pratt &Tye-Murray, 1997). Concerning the temporal aspects of vowel production, a significantly longer vowel duration has been well reported in this population (Anusha et al., 2010; Binos et al., 2020; Deepthy, & Sreedevi, 2018; Rohini & Premalatha, 2011; Srividya & Premalatha, 2016; Yang et al., 2015; Yang & Xu, 2017). The increase in vowel duration correlated well to the degree of openness of the oral cavity for the group with HI; the open vowel /a/ generally showed the longest duration and the close vowel /i/, the shortest. Also, the ratio of duration of long and short vowels was found to be higher in the CI group for the vowels /o/ and /u/ (Deepthy, & Sreedevi, 2018). In TDC, the duration of long vowels was twice that of short vowels whereas it was thrice in CI group (Anusha et al., 2010 in Kannada; Deepthy & Sreedevi, 2018 in Malayalam).

Likewise, longer word duration has been documented in children with CI compared to TDC (Anusha et al., 2010; Rohini & Premalatha, 2011; Srividya & Premalatha, 2016; Uchanski & Geers, 2003). It has been observed that the duration of vowel segments in the CVC words account for a larger percentage of the word duration (Uchanski & Geers, 2003).

A longer vowel and word duration could be attributed to various reasons. It could be due to the adaptive strategies used by children using CI to maximize the tactile and proprioceptive channels in the absence of auditory feedback for rapid smooth production of complex motoric sequences of speech (Higgins et al., 1999; Svirsky et al., 1992). Increased duration also suggests that children using CI may need more time to form the articulatory gestures and to travel from one target to the other. It could also be reasoned out that the speech model provided by the parents or caregivers might be exaggerated to acquire a better production which results in prolongation of vowels. Increased duration is also generally viewed as a marker of a less mature movement generator (Smith, 1978; Smith & Goffman, 1998). Therefore, with further refinement in the articulatory mechanism, the durational aspects of speech of CI users are expected to approach normal limits compared to TDC (Dawson et.al, 1995; Deepthy & Sreedevi, 2018; Uchanski & Geers, 2003).

2.6.1.2. Stops.

Among the temporal characteristics of stops, Voice Onset Time (VOT) has been extensively studied across languages in children using CI. Short term and long term advancements in the production of distinct voicing cognates as evidenced from VOT were reported in children after implantation (Aksoy et al., 2017; Blamey et al., 2001; Blamey et al., 2001; Deepthy & Sreedevi, 2019a; Higgins et al., 2003; Horga & Liker 2006; Kishon-Rabin et al., 2002; Serry & Blamey, 1999; Uchanski & Geers, 2003). A number of researches have implied that VOT durations were closer to the normal hearing peers (Aksoy et al., 2017, Anusha et al., 2010; Baudonck et al., 2010; Bharadwaj & Graves, 2008; Deepthy & Sreedevi, 2019a; Grandon et al., 2017; Kant et al., 2012; Kishore et al., 2018; Uchanski & Geers, 2003; Umat et al., 2015). The duration of implant use was found to be a significant contributor to the near-normal VOT values. Normalization of VOT values were obtained at least after two years of implant experience and intensive aural-oral rehabilitation (Deepthy & Sreedevi, 2019a; Kant et al., 2012). In a longitudinal study, Higgins et al. (2003) reported that during the first few years after implantation children had difficulty in controlling the onset of voicing for voiceless consonants. Even after several years of implantation, a shorter than normal VOT was observed. At the same time, abnormally long VOTs were noted in a few participants.

Findings specific to voiced and unvoiced stops are also described. For unvoiced stops (pooled for place of articulation), a shorter than normal VOT was observed in children using CI (Horga & Liker, 2006; Koupka et al., 2019). This may relate to ongoing developmental changes in children with lesser implant experience (Okalidou, 2010). However, longer VOT for unvoiced stops and shorter VOT for voiced stops were documented for French speaking children with CI compared to normal hearing controls (Scarbel et al., 2013). They interpreted their findings to suggest exaggeration of the voicing contrast between voiced and voiceless stops by children with CI.

Differences in VOT values were observed as a function of place of articulation. It was found that the pattern of VOT across places of articulation in children using CI was similar to that of TDC (Deepthy, & Sreedevi, 2018a; Koupka, 2019). VOT of unvoiced stops increased from bilabials/ dentals to velars in children using CI (Cho & Ladefoged, 1999; Fourakis, 1986; Grandon et al., 2017; Morris et al., 2008; Nicolaidis, 2002; Peterson & Lehiste, 1960; Volaitis & Miller, 1992; Whiteside & Marshall, 2001). For voiced consonants, there was a tendency for the VOT to decrease from bilabials to dentals to velars (Helgason & Ringen, 2008). However, in south Indian languages like Malayalam the increasing order of VOT concerning the place of articulation in children using CI is as follows: alveolars < bilabials < velars (Deepthy & Sreedevi, 2019a). Another study found longer VOT values for anterior unvoiced stops (/p/ and /t/) and shorter VOT for posterior /k/ in children using CI when compared to TDC (Umat et al., 2015). The possible explanation for this finding could be the difficulty in perceiving the cue for a posterior sound like /k/ which requires refinement in the coordination and timing between oral and laryngeal systems. However, the place feature is acquired relatively early because the frequency cue required for distinguishing place of articulation is provided by CI.

Other acoustic measures of particular interest are burst duration (BD) and closure duration (CD). The burst duration in children using CI was found to approach normal values except for /g/. The voiced velar /g/ exhibited significantly longer BD compared to TDC. On close observation, even though non-significant, other stop phonemes also demonstrated slightly longer values for BD across different places of articulation (bilabial, alveolar and velar). BD was found to increase from bilabials to alveolars and velars for both children using CI and TDC (Deepthy, & Sreedevi, 2019a).

The closure duration in children using CI was found to be shorter for voiced than unvoiced stops (Deepthy & Sreedevi, 2019a in Malayalam) which is in agreement with other studies on TDC (Lisker, 1957; Luce & Charles-Luce, 1985; Savithri, 1996). The values were found to be significantly longer for the bilabial /p/, /b/, retroflex /ʈ/, and dental /t/. Similar findings were reported in Croatian language for /t/ and /d/ phonemes (Horga & Liker, 2006). The increased duration manifested in children using CI is possibly due to the difficulty in coordinating the respiratory and phonatory systems resulting in longer closure duration prior to the articulatory release. In terms of place of articulation, CD was found to be longest for alveolars followed by bilabials and velars in both CI group and TDC (Deepthy & Sreedevi, 2019a).

2.6.1.3. Nasals.

The waveform of a nasal would exhibit reduced amplitude and a smoother periodic waveform shape relative to the subsequent vowel sound (Uchanski & Geers, 2003). The nasal murmur holds static cues for perception of place of articulation in nasal consonants (Ohde, 1994). However, the perception of nasal consonants are difficult for individuals with hearing loss and can have perceptual confusions with other sounds like stops (Han et al., 2017; Healy et al., 2014). Although nasal consonants are rich in dynamic and static cues, there is a dearth of published research on the production of nasal consonants in children using CI.

Malayalam has the highest number of places of articulation (six) for nasals compared to any of the world’s languages (bilabial /m/, dental /n̪/, alveolar /n/, palatal /ɲ/, retroflex /ɳ/, velar /ŋ/) (Ladefoged & Maddieson, 2008). Moreover, the number of nasal consonants and the frequency of occurrence of nasals are reported to be high in the conversational speech of native Malayalam speakers (Irfana & Sreedevi, 2013). Inaccurate production of nasal consonants can lead to poor speech intelligibility in children using CI. Deepthy and Sreedevi (2019c) investigated the acoustic characteristics of nasals in Malayalam speaking CI users which revealed that the mean values of nasal murmur were comparable to that of TDC. However, the nasal consonant duration of all nasal phonemes in the CI group were observed to be significantly longer for bilabial /m/, palatal /ɲ/ and retroflex /ɳ/.

2.6.1.4. Fricatives and Affricates.

Fricatives and affricates are the phonemes that are challenging to acquire and produce accurately by young children who use CIs, a finding that has been consistent across languages (Ingram et al., 2001; Liker et al., 2007; Mildner & Liker, 2008; Mildner et al., 2006; Peng et al., 2008; Serry & Blamey, 1999; Van Lierde et al., 2005). Compared to children with normal hearing, children using CI demonstrate more difficulties in perceiving and discriminating fricatives (Hedrick et al., 2011; Giezen et al., 2010). This may be partially caused by the poor spectral resolution of the CI devices through which the ‘place’ features are transmitted (Tyler & Moore, 1992). In addition, certain fricatives such as /s/ contain spectral energy concentration in a relatively high-frequency region, which is out of the typical frequency limit of CI (Yang et al., 2017).

The perception and production of fricatives /s/-/ʃ/ contrast are extensively investigated in English. The findings suggest that CI children were less capable of producing /s/-/ʃ/ contrast compared to TDC. Liker et al. (2007) examined the acoustic characteristics of fricatives produced by Croatian-speaking children with CIs at three-time points over a 20-month period post implantation. They found that the frequency range of /s/ and /ʃ/ showed significant overlap in the CI users. They produce less contrast between the spectral peaks of fricatives so that the distinction is less clearly rendered (Todd et al., 2011). Moreover, there was a downward shift in infrequency of the first spectral moment of /s/ which results in poor distinction between /s/ and /ʃ/ (Liker et al., 2007; Mildner, & Sindija, 2007; Neumeyer et al., 2015). The reduced auditory input and feedback in children using CI affect the production of fricatives not only from an acoustic point of view (Neumeyer et al., 2015), but also at the phoneme level (Salas-Provance et al., 2014).

The parameter, which is of particular interest in the present study is frication and affrication duration. Noise duration does provide a robust cue to the voicing distinction in syllable-initial position, with voiceless fricatives having longer noise durations than voiced fricatives. Noise duration does not reliably distinguish place of articulation in fricatives. Even though CIs are known to provide a greater amount of spectral information in the high frequencies relative to low frequencies, the spectral resolution needed to differentiate place of articulation of fricatives is still a challenge for CI users (Loizou, 2006; Moon & Hong, 2014; Rubinstein, 2004). As a result, children with CIs are commonly reported to produce neutralized or less contrasted fricatives (Liker et al., 2007; Mildner & Liker, 2008; Peng et al., 2008; Todd et al., 2011), sometimes even yielding atypical error patterns.

Duration of affrication was found to be significantly longer in CI group than in the TDC (Horga et al., 2002; Liker et al., 2007; Mildner & Liker, 2003). Affricates were more often substituted by fricatives, stops, or even unidentifiable fricative noise, than pronounced correctly. The duration was found to be decreasing and approaching near normal values with intensive therapy in which more normalization was noticed for palatal /c/ (Horga et al., 2002; Mildner & Liker, 2008). Li et al. (2017) indicating that for children with CIs, the temporal cues like duration and rise time provided more information to differentiate fricatives from affricates.

The benefit of longer implant experience on the production of fricatives could only be commended in light of the limitations of the cochlear implant. A CI does not transmit every fine-grained acoustic cues of affricates and fricatives that leads to difficulties in perception of high-frequency sounds (Mildner et al., 2006; Van Lierde et al., 2005). Moreover, early implantation and longer implant experience would improve certain aspects of fricatives, although these shortcomings will be difficult to overcome for the fricatives as a whole. Whereas, the acoustic cues required for the production of other sounds like stops or nasals are better perceived and produced (Mildner et al., 2006; Uchanski & Geers, 2003).

2.7. Articulatory Acquisition and Accuracy in Typically Developing Children

2.7.1. Articulatory Acquisition in Typically Developing Children

The most commonly produced consonants during the production of first words include /b/, /d/, /m/, /n/ and /w/ (Iyer et al., 2017; Stoel-Gammon, 2011). During the initial period of speech acquisition, children produce labial and coronal consonant place, stop and glide manners, and low, mid, front and central vowels (Davis et al., 2003; Kent & Bauer, 1985). Phonemes that require regulation of tongue placement such as dorsal, liquid and fricative consonants and back vowels (Kent, 1992) are reported to be rare in early sound inventories. Nasals, stops, glides are acquired earlier, and affricates and fricatives are acquired later (Bauman-Waengler, 1994; Templin, 1957). The unvoiced consonants are produced more accurately than voiced consonants. In terms of place of articulation, anterior sounds tended to be acquired earlier than posterior sounds. Overall, most typical children were able to produce /p, b, m, n, h, w/ by age three and produce all English consonants by age 8 (Smit et al., 1990; Templin, 1957).

Extensive studies on articulation acquisition have been carried out in several Indian languages also; Kannada (Deepa & Savithri, 2010; Prathima & Sreedevi, 2009; Sridevi, 1976; Tasneem, 1977), Tamil (Thirumalai, 1972; Usha, 1986), Bengali (Banik, 1988), Telugu (Padmaja, 1988) and Malayalam (Divya & Sreedevi, 2010; Maya & Savithri, 1990; Neenu & Sreedevi, 2011; Vipina & Sreedevi, 2011; Vrinda & Sreedevi, 2011). From the above studies, it can be concluded that speech acquisition followed a similar pattern as in English and most of the sounds were acquired earlier in the Indian languages. As the language of particular interest for the present study is Malayalam, a couple of existing studies on the acquisition of speech sounds are discussed in detail.

As part of the development of an articulation test battery, Maya and Savithri (1990) studied the articulatory acquisition in 3-7-year-old Malayalam speaking children. The findings revealed that all vowels were acquired by age 3. Most of the consonants were acquired by age three, except fricatives /s/, lateral /l/, trill /r/, flap /r/ and aspirated phonemes. Unaspirated stops were the phonemes acquired first, followed by fricatives, affricates and aspirated stops. Children acquired articulation of /s/, /r/, /l/, /f/, /c/, and /j/ by the age of 3-3.6 years. Unaspirated stops were acquired earlier than aspirated stops. Divya and Sreedevi (2010) concluded that all the vowels in Malayalam were acquired by the age of 2.3 years except /u/ and /u:/ which were mastered by the age of 3 years.

Later Malayalam Articulation Test (MAT) was revised by Neenu et al. (2011). The results revealed that most of the consonants achieved 90% mastery by 4 years of age. Considering the place of articulation, bilabials, labiodentals, dentals and velars were acquired first compared to alveolars, palatals, retroflex and glottal consonants (Neenu & Sreedevi, 2011). The consonants acquired during this age were /k/, /g/, /t/, /n/, /p/, /b/, /m/, /ʈ/, /v/, /j/, /ɲ/, /ŋ/. This finding is in agreement with Divya and Sreedevi (2010). Vipina and Sreedevi (2011) investigated the phoneme acquisition of 4-5 year old children. The phonemes that reached 90% criteria of accuracy were /ɖ/, /s/, /f/, /r/, /ʂ/, /ʐ/, /ɳ/, /R/, /ʃ/, /c/, /ɟ/, /ɭ/. Similarly, Vrinda and Sreedevi (2011) found that most of the singleton consonants were mastered by 5.3 years except for aspirated consonants and glottal /h/. It was also noted that unaspirated phonemes were acquired earlier than aspirated phonemes and medial clusters were acquired earlier than initial clusters (Neenu et al., 2011).

Compared to singleton consonants, consonant clusters (CC) require a longer time to acquire (McLeod et al., 2001a; Priester et al., 2011; Waring et al., 2001). Acquisition of clusters was studied in Indian languages. Divya and Sreedevi (2010) studied the acquisition of CC in Malayalam in the age range of 2-3 years and reported that none of the clusters reached 75% criteria by three years of age. At 2.9 years children began to produce clusters with substitution errors. For e.g. Vrinda and Sreedevi, (2011) reported that by the age of six years, 14 out of 15 clusters studied met 90% criteria both in initial and medial position. Also, the common errors found were cluster reduction followed by epenthesis and substitution (Vrinda & Sreedevi, 2011). Phonotactic development of Kannada speaking children in the age range of 0-5 years was studied by Rupela and Manjula (2006). It was found that medial geminate clusters were observed to be acquired first (12-18 months). CC acquisition were also studied in Kannada (Deepa & Savithri, 2010; Prathima & Sreedevi, 2009), Telugu (Neethi Priya & Manjula, 2007; Padmaja, 1988), and Benagli (Banik, 1988).

2.7.2. Articulation Accuracy in Typically Developing Children

Vowels are the most earliest acquired sounds and are reported to be accurate even in early words (Davis & MacNeilage, 1990; Paschall, 1983; Shibamoto & Olmsted, 1978). Greater accuracy for front and central, high and mid vowels is consistently reported (Davis & MacNeilage, 1990; Paschall, 1983; Shibamoto & Olmsted, 1978). Vowel substitutions were six times more prevalent than omissions (Paschall, 1983). Substitution of neutralized vowels or neighboring vowels in the vowel space, particularly those lower and more front than the target, (Davis & MacNeilage, 1990) is reported. In English, phoneme acquisition is investigated since 1930s. The early acquired stops, nasals and glides, were reported to be the most accurately produced consonants (60%) and liquids, fricatives and affricates were the most misarticulated sounds in English (Ferguson & Farwell, 1975; Shibamoto & Olmsted, 1978). Overall consonant accuracy increased from 53 % to 84 % (1.6-3 years) (Campbell et al., 2007; Stoel-Gammon, 1985). By the age of seven years, children displayed around 97% consonant accuracy (Campbell et al., 2007). They could produce all the sounds correctly by eight years (Poole, 1934; Templin, 1957). Children took more time to achieve mastery for fricatives (Fudula & Reynolds, 1986) and affricates (Templin, 1957).

Consonant clusters (CCs) are one of the last phonetic structures to be acquired by children in the course of phonological development (Adi- Bensaid & Ben- David, 2010; Allerton, 1976; Grunwell, 1981; Ingram, 1989; Preisseret al., 1988). In English-speaking typical children, word-initial consonant clusters emerge approximately by around age two and are produced with greater accuracy as age increases (McLeod et al., 2001b; Phoon et al., 2015). The most common error reported during cluster acquisition is cluster reduction, whereby two or three elements in the cluster are reduced to one or two (Ben-David, 2006; Demuth & McCullough, 2009; Kirk, 2008; McLeod et al., 2001; Smit, 1993; Wyllie-Smith et al., 2006).

Greenlee (1974) described four stages in the acquisition of CC in TDC, (1) both consonants are deleted (complete deletion), (2) only one consonant is produced (cluster reduction), and (3) both consonants are produced, but one or both are produced inaccurately (cluster simplification). These errors typically co-occur before fully accurate production (Ben-David, 2001; Jongstra, 2003; McLeod et al., 2001a; McLeod & Hewitt, 2008).

Stage 1: Deletion of the Entire Cluster.

During the first attempts to produce target clusters, children deleted the entire cluster. However, Ingram (1989) reported this to be an uncommon stage, but was supported by other studies (Ben-David, 2001; Demuth & McCullough, 2009; McLeod et al., 2001; Smith, 1993; Wyllie-Smith et al., 2006).

Stage 2: Cluster Reduction.

During this stage of CC acquisition, children reduced the cluster to a single consonant (a process specific to clusters). A pattern in deletion of the cluster was noted based on the target cluster in C_1 and C_2 position (C_1 and C_2 refer to the first and second consonants of the target cluster respectively).

(i) C_1 Deletion: When the second consonant of the target cluster (C_2) was a stop, fricative or nasal consonant, children tended to delete the first consonant (C_1) from the cluster and produce C_2, regardless of the type of consonant in C_1 position (e.g., in Malayalam, /ku:lə/ for /sku:lə/). Thus, if the target cluster is obstruent–obstruent or obstruent–nasal, then C1 was deleted.

(ii) C_2 Deletion: When the cluster included liquids in C_2 position (obstruent–liquid), children tended to delete the liquids and produce the obstruents (e.g., in Malayalam, /pa:və/ for /pra:və/).

There are some phonological models which try to predict the deletion patterns in clusters. Ingram (1989) suggested a model related to the markedness value of the individual consonants in the cluster. According to this model, the less marked consonant in the cluster is the one produced. For example, if /s/-plosive is the target cluster, then C_2 is produced (plosive), or /s/-nasal is the cluster, nasal is produced (C_1 is deleted), because stops, nasals, and glides are less marked than liquids and fricatives. That is, the markedness scale of consonants is in the following order: stops, nasal, glides < fricatives, liquids, where a comma indicates no distinction.

Another model refers to sonority-based selection, which indicates that if the consonant in the onset is less sonorous, the less marked the onset is (Barlow, 2005; Fikkert, 1994; Gierut, 1999; Gnanadesikan, 2004; Lukaszewicz, 2007; Ohala, 1999; Pater & Barlow, 2003; Wyllie-Smith et al., 2006). Sonority refers to a resonant property with respect to the degree of constriction. The more constricted the consonant is (stops > fricatives > nasals > liquids), the less sonorous it is. According to sonority based selection, it is assumed that children will prefer the least sonorous segment of the cluster over the more sonorous one (/s/-stop-stop, /s/-nasal-/s/).

A third probable explanation is based on contiguity. The contiguity principle states that segments that are adjacent in the input should be adjacent in the output (McCarthy & Prince, 1994). A consonant adjacent to a vowel is perceptually more salient than a consonant near to another consonant due to the sharp transition (Steriade, 2001). According to contiguity principle children will prefer producing the second consonant of the cluster. For example, if the target CC is /sp/ in the word /spu:ɳə/, children omit C1 and produce it as /pu:ɳə/ (Yildiz, 2005). In the case of stop-fricative clusters (e.g., /kʂama/ ‘patience’ in Malayalam), the markedness and the sonority based onset selection accounts predict the realization of C_1, while the contiguity predicts the realization of C_2.

(iii) Coalescence: Another process reducing the target cluster to one consonant was coalescence, in which the children combined features from both consonants of the target cluster to a single consonant that differs from both consonants (e.g., /fo:ɳ/ for stone).

Stage 3: Cluster simplification.

In this stage, both consonants of the cluster are produced, although both consonants are not always produced correctly (e.g., /blɛd/ for bread) (Greenlee, 1974).

Ben-David (2001) described two more additional stages in the acquisition of CC. They were *reduplication* (described as the second stage) in which the word-initial cluster was replaced by singleton onset (e.g., /ɖe:ɖu/ for /ble:ɖ/) and *attempts to produce both consonants* in which typical children apply epenthesis and metathesis during the production word-initial consonants. Grunwell (1987) suggests that the process of cluster reduction disappears by the age of four years. Later, errors consisted of cluster simplifications. However, Vrinda and Sreedevi (2011) found that cluster reduction followed by epenthesis and substitution errors were prevalent in 5-6 year old Malayalam speaking children. Typically, two-element consonant clusters (e.g., /sp, st, sk/) are mastered before three-element consonant clusters (e.g., /spr, str, skr/). Clusters containing fricatives (e.g., /fl/) usually are more difficult than clusters containing stops (e.g., /kl/) (McLeod et al., 2001a).

2.8. Articulatory Acquisition and Accuracy in Children using Cochlear Implant

2.8.1. Articulatory Acquisition in Children using Cochlear Implant

Articulatory acquisition in children using CI is reported to be systematic, but slower than in TDC (Blamey et al., 2001; Serry & Blamey, 1999). As CI conveys both temporal and spectral information in addition to intensity cues, lesser reliance on the kinesthetic and visual cues are exhibited. This results in better performance of all the phonemes, especially for the posterior (less visible) and unvoiced sounds (Blamey et al., 2001; Warner-Czyz & Davis, 2008). Overall, pediatric CI users exhibit acquisition of new sounds within six months of device use (Ertmer & Goffman, 2011;

Ertmer et al., 2012; Iyer et al., 2017; Sabri & Fabiano-Smith, 2015; Schauwers et al., 2004; Serry & Blamey, 1999; Warner-Czyz & Davis, 2008). Within the first year of CI use, there was an increase in the diversity of vowels and diphthongs (Ertmer, 2002). Within 24 months of CI use, the consonant inventories include /b/, /m/, /d/ and /n/ (Blamey et al., 2001; Blamey & Sarant, 2013; Serry & Blamey, 1999) and within four years of device experience the inventories expanded to include all bilabial and alveolar stops (except /t/) as well as the fricatives /ʃ/, /v/ and /f/ (Serry & Blamey, 1999).

The advantage of CI was also indicated by rich inventory of speech sounds in two years post implant case study by Chin and Pisoni (2000). The limited diversity of consonant repertoire expanded primarily from labials and nasals (Von Hapsburg, 2003) to include coronal and dorsal place (Blamey et al., 2001; Chin & Pisoni, 2000; Ertmer & Mellon, 2001; McCaffrey et al., 1999) and fricative, stop and glide manner (Blamey et al., 2001; Chin & Pisoni, 2000; Ertmer & Mellon, 2001) post implantation. Another study reported that children with CI started to produce stop consonants including /b/ and /m/ and added /p/, /d/, /n/, /j/, /w/, /t/, /k/, /n/ and /g/ over the 2 years of implant use. They have also found that the performance was on par or even higher than their typically developing peers (Iyer et al., 2017). Also, an increase in diversity across various consonant features (Blamey et al., 2001, Osberger et al., 1991; Tobey et al., 1994, Sevinc et al., 2009) as well as high level of accuracy (Bouchard & Normand, 2007) has also been documented.

2.8.1.2. Atypical Acquisition of late Emerging Phonemes.

The acquisition of late-emerging sounds was reported to be atypical in young CI users especially for fricatives and affricates. Ertmer and Goffman (2011) postulated three factors could influence the order of consonant acquisition after CI activation: (1) the perceptual characteristics of the CI signal. The CI signal provides artificial representation of speech features in which some consonants might be more salient than others. This finding is supported by high accuracy scores of late acquiring phonemes (fricatives-/ʃ/, /z/ and affricates-/c/, /ɟ/) compared to that of glides, liquids (/l/), and unvoiced, low-intensity fricatives (/f/ and /s/). Therefore, these phonemes would require relatively greater amounts of auditory training. (2) An atypical overlap in perceptual and production development. Children using CI begin to develop an awareness of the acoustic features of vowels and consonants at the same time as they begin to say words (Ertmer & Inniger, 2009; Nikolopoulos et al., 1999). This unusual overlapping of speech perception and production could impact the order of consonant emergence and stabilization. (3) Effects of intervention. Unlike children with normal hearing, children using CI undergo intensive auditory-verbal rehabilitation. The order in which consonants are introduced and trained during intervention sessions might influence the accuracy and variability of speech productions. This factor was shown to have a major influence on the order of phoneme acquisition (Serry & Blamey, 1999).

2.8.2. Articulatory Accuracy in Children using Cochlear Implant

Articulatory accuracy in children using CIs has been widely investigated (Brown & McDowell, 1999; Ertmer & Goffman, 2011; Leigh et al., 2013; Mildner & Liker, 2008; Moore et al., 2006; Schorr et al., 2008, Spencer & Guo, 2013; Tomblin et al., 2008; Turgeon et al., 2017). A significant improvement in overall production accuracy of both vowels and consonants, within a year of device use (Warner-Czyz & Davis, 2008; Warner-Czyz et al., 2010) has been documented. Children using CI exhibits greater diversity and accuracy in sound inventory than HA users (Geers & Tobey, 1992; Serry & Blamey, 1999) even with respect to less visible place features, complex manner features and voicing features (Tobey et al., 1994; Uchanski & Geers, 2003). Phoneme accuracy was also found to be positively correlated with the frequency of occurrence of a phoneme in a particular language (Faes et al., 2017; Han et al., 2015). Relatively less occurrence of phonetic errors including substitution, omission and distortion and phonological errors such as stopping, backing and cluster reduction is manifested in CI users compared to HA users (Asad et al., 2018; Van Lierde et al., 2005). Another study reports that devoicing, cluster reduction and deletion of final consonants were the most common phonological processes in CI (Baudonck et al., 2010).

There are studies that documented consistently lower accuracy for pediatric CI users in their speech production skills compared to TDC (Tobey et al., 2011; Tomblin et al., 2008; Gillis, 2017). Articulatory errors are generally explained in terms of SODA (substitution, omission, distortion, & addition) errors. Substantially more distortion errors in proportion to all other consonant errors are reported. However, few findings reveal that substitution errors were the highest and nasal-stop substitutions were the most common (Han et al., 2017; Moreno-Torres & Moruno-Lopez, 2014; Spencer & Guo, 2013).

Vowels were more accurately produced compared to consonants. Better vowel production is noted as a consequence of early acquisition (Ertmer, 2001) and the general acoustic or articulatory properties of vowels. Vowels are more intense and are of longer duration than consonants, and it is considered that vowels are more easily perceived with residual hearing and can be cued by comparatively simpler and slower changes of acoustic patterns. In contrast, consonants are weaker in intensity, higher in pitch, and shorter in duration: therefore, children with HI tend to produce more consonant errors than vowel and tone errors (Khouw, 1994). They are among the first phonemes to be acquired after implantation. Vowels differentiate from neutralized qualities (mid, central) pre-implant (Ertmer, 2001; McCaffrey et al., 1999) towards increased use of front vowels and high, mid and low height dimensions post-implantation (Blamey et al., 2001; Ertmer, 2001; McCaffrey et al., 1999). When substitution errors occurred in vowel production, children using CI substituted the target vowel with low- mid vowel /a/ (Adi-Bensaid, & Tobin, 2010). Even though considerable progress is noted in vowel production, children with CI produced moderately lower vowel accuracy scores (79%–83%) compared to their peers (98%–99%) even after 2 years of CI experience indicating a not fully stabilized or immature vowel production system (Ertmer & Goffman, 2011).

The consonant errors in children using CI are described in terms of place, manner, voicing and phoneme position in the upcoming section of review. An earlier study suggested that articulation errors in CI children generally differ from the target by only one feature (voicing, place or manner of articulation). Finally, errors of manner and voicing predominate over errors of place of articulation (Carr, 1953; Oller et al., 1978; Smith, 1975; Smith, 1972).

2.8.2.1. Errors of Place of Articulation.

Compared to other places of articulation, labials are the most correctly produced speech sounds. Also, labials that are highly visible had the highest production rates (Bauchard et al., 2007; Serry & Blamey, 1999; Tye-Murray et al., 2011) followed by labiodentals, alveolars, velar and palatals (Tobey et al., 2007). This ordering models a continuum of consonant visibility and supports the findings of other investigations (Ertmer & Mellon, 2001). Most of the early emerging sounds have visible places of articulation and could be easier to perceive and produce because of a combination of auditory and visual cues. As a result, these phonemes become consistently correct soon after implantation.

Some mid- and later acquired consonants are produced centrally (/l/, /s/, and /z/) and do not provide salient visual cues. These consonants might be acquired later than those with stronger visual cues (Stoel-Gammon, 1988). The production of alveolars and palatals /t, s, z, c, ɟ, θ/ remains associated with difficulties, such as distortions, substitutions, and omissions, because of the concentration of energy at relatively high frequencies and low-intensity levels (Blamey et al., 2001). Likewise, Blamey et al. (2001) reported confusions in perception and production of alveolars, palato-alveolar phonemes like /t, s, c, z/ which constitute similar acoustic-phonetic characteristics. This could be attributed to the similarity in the energy concentrations at high frequencies and relatively low-intensity levels. Thus the perceptual similarity of these phonemes contributes to their late, slow development. This is in agreement with Warner-Czyz et al. (2010), and Tobey et al. (2007) who postulated that phonemes which are less salient and distinguishable via the CI signal could lead to difficulty to discriminate, identify, and produce accurately. The articulatory movements for both alveolar and velar sounds are visually obscure compared to bilabials. One reason for the compromised production of alveolars is that more sounds are produced in the middle than in the back of the mouth. Because of this, precise positioning of the articulators is necessary in order to differentiate the sounds correctly with a medial place of articulation (Lass, 2014).

2.8.2.2. Errors of Manner of Articulation.

With respect to manner of articulation, children using CI were typically most accurate for early developing sounds such as stops, nasals and glides and least accurate for later developing sounds such as affricates (Ertmer et al., 2012; Warner-Czyz et al., 2010). The high visibility and simple motoric characteristics of the labial stop consonants could be the reasons for their relatively early emergence in the speech of children with hearing loss as well as TDC (Kent, 1992). Because of an added privilege of kinesthetic and tactile cues, accurate production of continuant consonants was also documented (Stoel-Gammon, 1988).

Investigations on production of manner features have suggested that stop consonants were the most accurately produced consonants, and fricatives the least accurately produced. Moreover, the substitution of fricatives by stop consonants is common in CI children (Bouchard & Normand, 2007; Kent, 1992). The sequence of phonemic development revealed that anterior sounds precede posterior ones, oral sounds precede nasal ones and stops precede fricatives (Peng et al., 2004; Tye-Murray et al., 1995). A study on consonant production in children using CI has found that the accuracy of consonants was as follows: Stops (52%), fricatives (54%), nasals (50%), and liquids (46%). Bilabial stops, glides, fricatives /f/ and /v/ were often produced correctly (Smith, 1975). Nober (1967) suggested that glides were most often correct followed by stops, nasals and fricatives. When there was an error production, children using CI tended to substitute a phoneme within the same sound class as that of the target phoneme i.e. obstruents in response to target obstruents (stops and fricatives) and sonorants in response to target sonorants (nasals and liquids). The children also tended to delete target sonorants more often than target obstruents (Dillon et al., 2004).

Perceptual confusions among similar consonants are one of the prominent features in cochlear implantees. A recent study has found that the most common consonant confusions were between consonants with the same manner and same voicing (For e.g., among the nasals, 81.2% were repeated as the same, or as another nasal). The highest proportion of consonant confusions was found for the lateral /l/, with a correct score of only 61.1%. The least common confusions were between consonants with a different manner and opposite voicing (Rødvik et al., 2019).

Research on the production of nasals has found that the nasal phonemes (bilabial /m/, alveolar /n/, velar /ŋ/), were often confused with one another by children using CIs. The authors opined that nasality could act as an obstacle to consonant recognition. This could be due to the prominence of low frequencies around 250 Hz in the nasal spectrum which is known as nasal formant or, the nasal murmur. It is a known fact that CIs provides low frequencies poorly compared to high frequencies (Caldwell et al., 2017). It has been stated that both formant transitions and nasal murmur are important to provide information on place of articulation (Kurowski & Blumstein, 1984). The lack of proper acoustic information could be the reason for nasal consonant confusions. Also, among the nasal phonemes, bilabial /m/ is the most accurately produced phoneme because of an added privilege of visibility or anterior production of the phoneme. Further, substitution of the alveolar nasal /n/ with bilabial /m/ is often found in children with CI (Boundack et al., 2010). The authors opine that these substitutions can be viewed as excessive distortions, as they cross phoneme boundaries. Additionally, the /n/-/m/ substitution supports the findings of previous studies that observed a preference for bilabial consonants (Oller et al., 1978; Smith, 1975; Stoel-Gammon, 1988). It was also noted that there were remarkable nasal-stop substitutions in the CI group (Han et al., 2017). Non-nasal phonemes were reported to be nasalized and nasal phonemes were often produced as stops (Smith, 1975).

Fricatives and affricates are among the last acquired and the most erred sound class in children with CI (Mildner & Liker, 2003; Mildner & Liker, 2008). The acquisition of alveolar fricatives was highly variable, even in children with normal hearing (Bauman-Waengler, 2000). In CI users, the accuracy of all fricatives were lower when compared to children with TDC (Gaul-Bouchard et al., 2007; Kim & Chin, 2008; Warner-Czyz & Davis, 2008), and the most frequent error for fricatives were stopping (Baudonck et al., 2010; Faes & Gillis, 2016; Flipsen & Parker, 2008; Gaul-Bouchard et al., 2007; Kim & Chin, 2008), omission (Faes & Gillis, 2016; Warner-Czyz & Davis, 2008), substitution of other fricatives (Baudonck et al., 2010; Dillon et al., 2004, Faes & Gillis, 2016) or errors in voicing (Kim & Chin, 2008). For children using CIs, the perception and discrimination of fricatives' places of articulation are more challenging than manners of articulation (Giezen et al., 2010).

Smith (1975) noted that affricates were never substituted for other consonants but tended to be substituted by one of their components, usually the plosive component. However, Mildner and Liker (2008) reported that affricates were most frequently substituted with a fricative. Among the fricatives, /s/ was produced with lower accuracy than other fricatives. Todd et al. (2011) found that across a group of four- to nine-year-old CI children, /s/ was produced with 62% and /ʃ/ with 82.5% accuracy. These accuracy rates were noted to be similar to those of TDC whose ages were matched to the CI children's duration of implant use, but were lower than those of age-matched TDC. The frequency range of /s/ and /ʃ/ showed considerable overlap in the CI children, which indicates less differentiation between these two fricatives.

In general, studies have shown that CI children show delayed consonant acquisition and less separation of fricatives compared to age- matched TDC (Liker et al., 2007). Substitution of /f/ for /s/ (Giezen et al., 2010; Todd et al., 2011) and /ʃ/ for /s/ (Liker et al., 2007; Uchanski & Geers, 2003) are widely reported. Transcription analyses have shown that children with CIs are typically more accurate on target /ʃ/ than target /s/ (Blamey et al. 2001; Giezen et al., 2010; Hedrick et al., 2011; Reidy et al., 2015; Serry & Blamey 1999). This distinct contrast between /s/ and /ʃ/ are produced as early as two years post-implantation, yet not as accurate as TDC (Grandon & Vilain, 2020). This finding differs from the findings of Mildner and Liker (2008) in which both alveolars (/s/) and post-alveolars (/ʃ/) were only produced distinctly after 46 months post- implantation. Palatal fricative /ʃ/ is probably one of the most over-represented segments in the speech of profoundly hearing impaired children. They frequently substitute it for /s/, /c /, and /ɟ/ / in addition to using it in its right place (Mildner & Liker, 2003).

The possible explanation for the difficulty in the production of /s/ was postulated by various authors. The auditory representation that a child learns is directly related to the auditory properties of the sound to which the child is been exposed to (Cristià, 2011). For CI users, there is greater dissimilarity between the auditory and acoustic properties of a sound, due to the CI processor's reduced spectral resolution and limited analysis bandwidth (Reidy et al., 2017). For fricatives, energy is most concentrated between 7 and 10 kHz for /s/ and between 4 and 6 kHz for /ʃ/ (Jongman et al., 2000; Li, 2012) and CIs deliver poorer frequency resolution for the higher frequencies. Therefore, children with CIs may have produced /s/ at lower frequencies resulting in error production. However, considerable improvements in speech perception and production of both fricatives and affricates have been reported with increase in duration of CI experience. A longitudinal study of over 46 months in Croatian speaking cochlear implantees, has found that fricatives /s/ and /ʃ/ started showing separation and the affricates /ts/ and /c/ were produced more accurately and closer to target articulations (Mildner & Liker, 2008). This is in agreement with earlier investigations reporting significant improvements for up to 5 years post-implantation (Kishon-Rabin et al., 2002).

2.8.2.3. Errors of Voicing.

Voicing is one of the key characteristics of consonant production. Reduced ability to contrast voiced and unvoiced consonants could affect speech intelligibility (Kent et al., 1989). Voicing control involves precise coordination between laryngeal and supra-laryngeal mechanisms. The complexity in achieving fine control of voicing in terms of motor control makes it one of the last acquired features in speech acquisition (Ingram, 1999; Kent, 1992). Voicing appears to be the unmarked member of the voicing contrast. In normal voicing contrast acquisition, unvoiced sounds emerge from the voiced (Flege & Eefting, 1986).

Errors of voicing were one of the most frequent types of consonant errors found in children using CI (Higgins et al., 2003; Ryalls et al., 2003; Tye-Murray et al., 1995; Tye-Murray et al., 1995). Cochlear implantation would contribute to developing distinct voicing cognates (Aksoy et al., 2017; Blamey et al., 2001; Horga & Liker, 2006; Kishon- Rabin et al., 2002; Serry & Blamey, 1999; Uchanski & Geers, 2003). After one year post-implantation, children produced more voiced plosives than their unvoiced cognates (Dillon et al., 2004; Tobey et al., 1991). The CI group correctly reproduced the voicing feature for voiced consonants higher than unvoiced consonants. An equal percentage of deletion of both voiced and unvoiced consonants are also reported (Dillon et al., 2004).

Few other studies have reported contrasting findings. There was a devoicing bias for the stops (Baudonck et al., 2010; Rødvik et al., 2019; Tye-Murray et al., 2011; Wieringen & Wouters, 1999). Confusions among unvoiced stops with different places of articulation were noted and voiced stops were confused with both unvoiced stops and voiced stops. For other phoneme classes, unvoiced consonants were most frequently confused with other unvoiced consonants and vice versa (Rødvik et al., 2019). This phenomenon of bias towards unvoiced stops was observed only in children using CI and hence probably is implant related. This may be linked to two main reasons: (1) Cochlear implants deliver F0 feature poorly for voiced sounds due to missing temporal information in the electrical signal and too shallow electrode insertion depth to cover the whole cochlea (Caldwell et al., 2017; Hamzavi & Arnoldner, 2006) and (2) VOT helps the perception of unvoiced stops much more easier than the voiced stops due to the aspirated pause between the stop and the following vowel in a VCV context (Rødvik et al., 2019).

2.8.2.4. Errors across Phoneme Position.

Progress in consonant production accuracy occurred in all word positions (initial, medial, and final) post-implantation (Dawson et al., 1995). However, initial consonants were more accurately produced followed by medial and final consonants (Ertmer et al., 2012). As final consonants were produced with the lowest accuracy, most of the studies have considered longitudinal comparisons of improvement in initial phoneme production accuracy. Production accuracy of initial CV syllables was found to be approximately 43% in children with 15 months of CI experience (Warner-

Czyz et al., 2010). Another study reported 60% accuracy after 2 years of device experience (Ertmer & Goffman, 2011). These findings further support an added value of implantation at a younger age (Connor et al., 2006) and higher articulation test scores are associated with younger age of implantation (Flipsen, 2011).

Murphy and Dodd (1995) reported that a high occurrence of deletions of final consonants was common in the speech of hearing-impaired children, compared to initial and medial, and this could be the reason for significantly more final consonant errors. The greater production accuracy of initial consonants compared to final consonants could be due to relatively greater perceptual saliency of initial consonants as evidenced from auditory perception studies (Redford & Diehl, 1999). He also found that initial consonants appeared to have relatively greater amplitude and acoustic distinctiveness than final consonants. These findings were in consonance with Gow et al. (1996) who suggested that word initials or onsets have more redundant and robust acoustic cues and are less subjected to phonological assimilation. The onsets may also “activate lexical representations which facilitate word perception, thus diminishing listeners’ dependence on acoustic-phonetic processing of the remaining segment of words”. These obvious perceptual advantages of initial consonants explain the relatively lower accuracy scores for medial or final consonants. In addition to these reasons, other factors also could contribute for CI users. These include the late acquisition of closed syllables (VC, CVC) than open syllables (CV, CVCV) in prelinguistic vocal development (Ertmer & Jung, 2012) and the impact of speech rehabilitation if lesser emphasis is on final consonants compared to the initial ones (Ertmer et al., 2012).

Atypical acquisition of final consonants is also widely reported. Redford and Diehl (1999) supports the fact that relatively more intense final consonants are easier to acquire than those of less amplitude. The author also suggests that duration of final consonants does not influence identification and acquisition of consonants. Therefore, consonants that can be intensified might have relatively greater saliency in the final position, making them easier for young CI recipients to acquire (Gow et al., 1996; Redford & Diehl, 1999). It is established that the acquisition of affricates in the word-final position could be difficult because they are not easily emphasized and comparatively have complex manners of production.

The relative low scores and atypical acquisition of final consonants suggests the importance to emphasize on final position and ordering target consonants during intervention. For example, rather than following a typical developmental order (Smit et al., 1990), affricates in the word-final position might be acquired more efficiently when introduced early in the training program since they were the least accurately produced compared to any other consonant. For one possible practical application, clinicians should focus on discrimination and identification of nasal and plosive substitutions. For instance, if nasal substitution is dominant, auditory training for reducing nasal substitutions would be an initial step to enhance speech perception ability. Because this strategy is able to reduce the highest error with accuracy at the beginning of auditory training, it will provide an effective training protocol for either clinicians or patients in terms of a shorter total training period and a saving of expenses (Han et al., 2017).

2.8.2.5. Cluster Production Accuracy in Children using CI.

Studies dealing with consonant cluster production of CI children are relatively less (Adi-Bensaid, & Ben-David, 2010; Chin & Finnegan, 2000; Dabiri et al., 2019; Faes & Gillis, 2017; Flipsen & Parker, 2008; Fulcher et al., 2014; Oller et al., 1978; Von Mentzer et al., 2015). Also, a quantified comparison between CI and TDC groups of children are missing in the literature. Cluster production accuracy in children using CI are generally described with respect to phonological processes and rarely in terms of phonological development stages (Ingram's 3 stages of CC acquisition). Research has shown that children using CI use the same phonological processes as TDC with respect to consonant cluster development (Ben- David, 2001). The most frequently occurring phonological process in children using CI is cluster reduction (Chin & Finnegan, 2000; Dabiri et al., 2019; Flipsen & Parker, 2008). The reduction/deletion patterns of the CI group exhibited an inclination towards the production of C_2 in all type of clusters (obstruent–obstruent, obstruent–glide, nasal–glide and obstruent–nasal clusters) except for obstruent-liquid clusters in which C_1 was preferred. This pattern of preference was similar to the typical acquisition (Ben-David, 2001). In addition, children with CI reduce consonant clusters for a longer period than their normal hearing peers.

The most interesting finding from researches is that CC production patterns exhibited by children using CI were similar to TDC (McLeod et al., 2001a; Waring et al., 2001; Adi-Bensaid & Ben-David, 2010; Faes & Gillis, 2017; Fulcher et al., 2014). However, accuracy of consonant clusters is lower in children using CI as compared to their normal hearing peers (Faes & Gillis, 2017; Von Mentzer et al., 2015). With an increase in hearing experience, children using CI were found to produce more consonant clusters more accurately (Chin & Finnegan, 2000; Dabiri et al., 2019; Faes

& Gillis, 2017). As hearing experience increases, child's awareness of cluster structure improves, and thus the use of cluster simplification is preferred over cluster deletion (Dabiri et al., 2019; Faes & Gillis, 2017). Chin and Finnegan (2000) examined the production of word initial CCs by children using CI through a picture-naming task. Findings revealed that about half of the clusters were produced correctly (48%). Remaining 34% of the clusters were produced with two segments where at least one segment was incorrect, 11% of the clusters were produced with one segment (followed sonority principle), and 7% had incorrect two-segment productions. The production pattern was found to be similar to normal acquisition. Few studies have reported the presence of reduplication in CI group. However, this was not indicated as a deviation from the typical acquisition (Adi-Bensaid & Ben-David, 2010; Ben-David, 2001).

From the review it is well understood that cochlear implantation leads to considerable improvements in speech production in children with hearing impairment. This progress is dependent on various subject and implant related factors. Moreover, the processing of speech signal via CI differs significantly from hearing aids and the output delivered to the auditory system from these devices is electrical and acoustic respectively. This inherent difference results in perceptual and production patterns that are unique to the device used (CI or hearing aid). Therefore, intervention goals taken up for one group may not be appropriate for the other. A comprehensive detailing (qualitative and quantitative) would help the clinician to choose and prioritize intervention goals. Furthermore, the effectiveness of speech therapy can be assessed only if the speech characteristics are properly documented. Therefore, a detailed profiling of acoustic and articulatory characteristics of speech is essential for better understanding of the prevalent deficits in CI population.

2.9. Assessment of Speech Characteristics in Children using CI

Both subjective and objective methods are adapted for the assessment of speech. Subjectively, speech production abilities are commonly assessed using standardized articulation tests and rating scales. The objective evaluation includes acoustic and physiological measurements (Kent, 1999).

2.9.1. Speech Elicitation and Analysis Procedures

Assessment of speech production skills employs variety of ways. This could vary with respect to elicitation tasks used and analysis procedures.

2.9.1.1. Speech Elicitation Procedures.

Speech production skills of children are assessed using a variety of speech elicitation tasks broadly categorized as imitative tasks, picture naming tasks (standardized articulation assessments), and spontaneous speech samples (Tobey et al., 1994; Tye-Murray & Kirk, 1993). There are potential advantages and disadvantages to each method of elicitation. In imitative tasks, a child is required to reproduce an adult model and need not involve knowledge of specific vocabulary items. But there are chances of the target phoneme to be exaggerated by clinician to facilitate improved production from the child (Tye-Murray & Kirk, 1993). Picture naming tasks generally comprise standardized articulation tests. It consists of single words or simple phrases and specific phonemes targeted in a variety of word positions. This is an efficient and relatively easy method for obtaining a sample of speech sound productions. Single words provide a discrete, identifiable unit of production that examiners can usually readily transcribe. Transcription time for the same size of sample is much less for single-word samples. Furthermore, use of one single-word list across multiple clients and probe points enhances intra-and inter client reliability, allowing identification of impairment and standard evaluation of outcomes over time (Masterson et al., 2005). It allows the SLP to obtain a percentile rank or standard score to compare the child's performance with same-age peers (Khan, 2002). However, some SLPs report of conducting additional analyses for the speech samples obtained for greater understanding of the extent of disorder. This may involve analyzing all consonants in all words produced during testing, not just those scored by the test (Bankson et al., 2013; Elbert & Gierut, 1986; Klein, 1984; Macrae, 2017).

Spontaneous speech samples are considered as one of the most representative elicitation methods since it allow a clinician to evaluate a child's ability to integrate language as well as the segmental and suprasegmental aspects of speech (Johannisson et al., 2014). Spontaneous speech samples provide the most comprehensive representation of a child's production ability but do not provide a clinician with the target. This factor becomes important when testing populations with atypical production ability, such as children with hearing loss, who include variations for different phonemes. Hence, imitative tasks and standardized assessments are often used for assessing speech production in children with hearing loss (Sundarrajan, 2015).

2.9.1.2. Analysis Procedures.

The methods generally employed for analysis of speech could be broadly classified into perceptual, acoustic and physiological measures. Most studies on post-implantation speech development have relied on the perceptual judgment of child's production. Perceptual assessments are carried out for analyzing the speech sound errors. For this purpose, a universal system for representing the child's utterances has to be adapted for effective communication within the professionals. The most common transcription system for recording sound errors is the International Phonetic Alphabet (IPA), which includes different symbols for each phoneme (International Phonetic Association, 2005; Tiffany & Carrell, 1977). There are generally two types of transcription, which includes broad and narrow phonetic transcriptions (Bauman-Waengler, 2008; Peña-Brooks & Hegde, 2007; Sundarrajan, 2015). Narrow transcription protocols are often preferred when planning treatment goals. Due to relatively high reliability of broad transcriptions, they are often chosen as the preferred transcription method in research studies of children using CIs. Though it lacks data necessary for preparing treatment goals, they are adequate for assessment purposes and to answer clinical research questions (Shriberg et al., 1997).

Speech sound errors or articulatory errors are predominantly motor-based errors and are generally classified as substitution, omission, distortion and addition errors. For children with multiple errors, effort should be made to identify commonalities across error productions or sound error patterns. Error pattern analysis provides a description of the child’s overall phonological system (Bernthal & Bankson, 2004) and has the potential for facilitating treatment efficiency. For example, if a child has eight speech sound substitutions reflecting three error patterns (e.g., stopping of fricatives, gliding of liquids, fronting), remediation would likely focus on the reduction of one or more of these phonological patterns. The modification of one or more speech sounds reflecting a particular error pattern frequently results in generalization to other speech sounds reflecting the same error pattern. Examples of methods of pattern analysis are Place-Voicing Manner, distinctive feature analysis, Phonological process analysis, Deep testing (McDonald, 1964), Phonotactic analysis (Velleman, 2002) etc.

One of the major concerns regarding perceptual assessment relates to accuracy. For this reason, perceptual judgements are occasionally supplemented with physiological measures (imaging, aerodynamic, kinematic measures) and acoustical measures. Acoustic analysis allows the clinician to have a quantifiable baseline for treatment follow-up. It provides two basic options: extraction of measures (fundamental frequency, frequency perturbation, and noise measurement) and spectrographic analysis (Behlau & Murry, 2012). The emergence of free acoustical analysis software such as Praat developed by Boersma and Weenink (2015) has made acoustic analysis by clinicians a simpler task. The main speech analysis features of PRAAT include waveform, spectral (including FFTs and spectrograms), formant, intensity, pitch, and voice (including jitter, shimmer, and additive noise) analyses. In particular, the advantages of acoustic measures include: (1). Are noninvasive (especially important for young children), (2). Are readily available as open access, downloadable computer software (Praat), (3). Provide measures that support clinical assessment and management (Carson & Ryalls, 2018). Other widely used software packages for acoustic analysis of speech includes Computerized Speech Lab (CSL-e.g. MDVP), Dr. Speech, Speech Filing System (Waveforms Annotations Spectrograms and Pitch-WASP), Wavesurfer, SIL Speech Tools (Speech Analyzer).

There is no single procedure for the assessment of speech production. Every method has its own advantages and disadvantages. The speech elicitation tasks used (single word, spontaneous speech or conversation) and analysis procedures followed (perceptual or instrumental) depends on the information required by a clinician for planning intervention goals. Combining objective assessments with perceptual methods would also help to identify perceptual difficulties of certain sounds at particular frequency regions. This would further help in re mapping the implant to maximize the output in the required frequency regions. It also aids in understanding the accuracy and naturalness of speech in terms of temporal and spectral characteristics and to prioritize goals accordingly. Finally, yet importantly, McCauley (1989) cautioned that the quality of clinical action depends upon the quality of measurement.

To summarize literature reports, cochlear implants are considered as the best rehabilitation option for children with severe to profound hearing impairment. Substantial improvements in all aspects of speech production are well reported in CI recipients compared to HA users. Speech of children using CI is reported to reach near normal values with increase in duration of implant use. However, difficulties specific to certain sound classes were observed as a result of the implant characteristics. For example, fricatives were noted to be the most difficult phoneme class in children using CI due to the implant's frequency resolution characteristics. Also more deficits in temporal parameters compared to spectral parameters were evidenced. Moreover, the majority of available research has focused mainly on the spectral analysis of speech. Other than VOT temporal aspects of speech production have received little attention in children using CI and even in TDC. This has to be addressed as timing may be the most critical factor in skilled motor performance like speech (Kent, 1976).

Additionally, there is a substantial increase in the number of CI recipients following evidence of better outcome and government schemes that provide financial support for surgery and intervention for a particular period. It is worth pointing out that till date there has been limited research on the acoustic and articulatory characteristics of speech of children using CI in Indian languages. Such research is important both from a theoretical and a clinical perspective, as it can provide insights that relate to the phonetic/phonological characteristics of particular languages (Nicolaidis & Sfakiannaki, 2007). Hence the motivation for the present study to investigate the acoustic and articulatory characteristics of children using cochlear implants was as such information can augment their speech intervention for achieving improved speech intelligibility.

Chapter 3: Methods

The aim of the present study was to investigate the acoustic and articulatory characteristics of Malayalam speaking children using cochlear implant and to compare the same with typically developing children in the age range of 4 to 8 years.

3.1. Study Design

The study adopted a standard group comparison design to examine the aim and objectives of the study. Sample size was calculated using G power software (Faul et al., 2007). The acoustic measures were analyzed after collecting speech samples from 10 participants. Mean and standard deviation obtained from the acoustic parameters were used to calculate sample size keeping alpha at 0.05 and power of test at 0.80. The obtained sample size was 30 for each group. Convenience sampling technique was used to recruit the participants.

3.2. Participants

A total of 80 Malayalam speaking children in the age range of 4.0 to 7.11 years were recruited for the study. Participants were divided into two groups: clinical and typically developing children. The clinical group consisted of 30 children (15 Boys & 15 girls) with congenital hearing loss fitted with multi-channel cochlear implant (CI). The clinical group was further divided into two subgroups based on the number of years of cochlear implant use. Subgroup I included participants with 2-3 years of cochlear implant experience in the chronological age range of 4.0-5.11 years (8 boys & 7 girls; Mean age=5.08 years, *SD*=0.72). Subgroup II included CI participants with 3-4 years of cochlear implant experience in the chronological range of 6.0-7.11 years (7 boys & 8 girls; Mean age=6.62 years, *SD*= 0.65). These participants were recruited from ENT hospitals and private speech and hearing clinics from the state of Kerala, India.

A total of 50 age-matched typically developing children (TDC) in the age range of 4.0 to 7.11 years were recruited. Participants were further divided into two subgroups with 25 participants each to match the clinical group based on their chronological age. Subgroup I (younger group) comprised of participants in the age range of 4.0-5.11 years (13 boys & 12 girls; Mean age=5.2 years, *SD*=0.63) and subgroup II (older group) comprised of participants in the age range of 6.0-7.11 years (12 boys & 13 girls; Mean age=6.9 years, *SD*=0.73). These typical participants were recruited from regular primary schools in Kerala. Participants of both groups were from the northern and central regions of the state of Kerala.

3.2.1. Participant Selection Criteria

3.2.1.1. Inclusion Criteria for Clinical Group.

a. Native speakers of Malayalam[3] and predominant exposure to Malayalam only
b. Diagnosed as congenital severe to profound hearing loss before CI surgery
c. No history of persisting middle ear problems
d. Unilateral cochlear implantation (fitted with Cochlear Nucleus Freedom CI24RE (ST)[4]
e. Bimodal fitting (use of a cochlear implant in one ear and a hearing aid in the opposite ear)

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[3] Malayalam is a Dravidian language primarily spoken in Kerala, a southern state of India. It has unique phonological characteristics with 11 vowels, five-stop places of articulation, six nasals (Asher & Kumari, 1997).

[4] Children fitted with Nucleus Freedom C124RE (ST) only were considered based on the availability of participants and to control implant related variables.

f. CI children having aided hearing threshold within the speech spectrum
g. Cochlear implantation by the age of 3 years
h. Minimum of two years of CI use
i. Undergone a minimum of two years of Auditory Verbal Therapy (AVT) at the time of participation in the study.
j. Uses 2-3 word sentences, and expressive vocabulary of 50-70 words which was assessed using Receptive Expressive Emergent Language Scale or Receptive Expressive Language Test- REELS (Bzoch & League, 1971)/ RELT (Savithri, 1986). These tests were administered for recruiting participants who meet the inclusion criteria and not for any further language comparisons.
k. Belonging to middle and/or upper-middle class family as assessed using the National Institute of Mental Health (NIMH) Socioeconomic Status Scale (Venketesan, 2011)
l. Absence of any co-morbid syndromic conditions, orosensory, motor, intellectual or any visual deficits

The demographic details of CI participants are provided in Table 3.1

3.2.1.2. Inclusion Criteria for Control Group.

a. Native speakers of Malayalam
b. Hearing sensitivity within normal limits with no persisting middle ear pathologies
c. No hearing, language, motor, oro-motor, or any cognitive impairments, ensured using WHO ten disability screening checklist (Singhi et al., 2007)
d. Belonging to middle and/or upper-middle class family as assessed using the National Institute of Mental Health (NIMH) Socioeconomic Status Scale (Venketesan, 2011).

Table 3.1

Demographic Details of Participants in the Clinical Group (CI)

Groups	*Sl. No. (Participants)*	*Age of identification of HL*	*Duration of hearing aid use*	*Pre-implantation intervention*	*Age of implantation*	*Years of CI use*	Language age	
							RLA	ELA
Subgroup I (4.0-5.11 years with 2-3 years of CI Experience)	1	1;5	1;5	1;3	3	2;9	48-54	42-48
	2	1	1;7	1;4	2;9	2;9	33-36	33-36
	3	1;8	1;1	1	2;9	2;2	42-48	42-48
	4	1;3	1	0;11	2;4	2;4	42-48	36-42
	5	1;5	1;1	0;11	2;8	2;6	36-42	30-33
	6	1;1	1;5	1;2	2;9	2;2	42-48	36-42
	7	1;5	1;4	1	3	2;8	36-42	30-33
	8	0;10	1	1	2	2;4	42-48	30-33
	9	1;7	0;10	0;9	2;6	2;5	42-48	42-48
	10	0;11	0;10	0;10	2;8	2;1	36-42	30-33
	11	1;2	0;9	0;8	2;2	2;2	42-48	42-48
	12	1;2	1;7	1;4	3	2;8	48-54	42-48
	13	1;3	1;6	1;5	3	2;2	36-42	30-33
	14	1;5	1;5	1;2	3	2;9	30-33	30-33
	15	1;6	1;5	1;3	3	2;8	42-48	36-42

Groups	*Sl. No. (Participants)*	*Age of identification of HL*	*Duration of hearing aid use*	*Pre-implantation intervention*	*Age of implantation*	*Years of CI use*	Language age	
							RLA	ELA
Subgroup II (6.0- 7.11 years with 3-4 years of CI Experience)	16	1;8	1;2	1	3	4	54-60	42-48
	17	1;3	1;4	1;1	2;10	3;11	42-48	42-48
	18	1;2	1;7	1;6	2;8	3;11	60-66	60-66
	19	1	1;6	1;3	2;7	3;10	54-60	48-54
	20	0;7	1;5	1;5	2;2	4	60-66	54-60
	21	1	1;5	1;3	2;7	3;9	54-60	42-48
	22	1;5	1;6	1;5	3	3;8	66-72	60-66
	23	1;2	1;8	1;6	3	4	66-72	60-66
	24	0;9	1;1	1	2;1	4	54-60	48-54
	25	1;7	1;3	1;1	3	3;7	42-48	42-48
	26	1	1;10	1;7	2;11	3;9	54-60	48-54
	27	1;5	1;2	1	2;8	3;7	54-60	42-48
	28	1	1;10	1;5	2;11	3;11	66-72	54-60
	29	1;3	1;7	1;4	3	3;9	48-54	48-54
	30	1	1;11	1;8	3	4	54-60	42-48

Note. HL= Hearing Loss, CI= Cochlear Implant, RLA=Receptive language age, ELA=Expressive language age, Age/duration is represented in years; months

3.3. Ethical Consideration

The study followed ethical guidelines as per ‘Ethical guidelines for bio-behavioral research involving human subjects’ framed at the All India Institute of Speech and Hearing, Mysuru (Basavaraj & Venkatesan, 2009) and was approved by the AIISH Ethical Committee before initiating the study. The participants were recruited for the study only after obtaining the written consent for participation from parents or caregivers (See Appendix A for participant consent form). They were explained the need, procedure and approximate duration of the assessment.

3.4. Procedure

The present study was carried out in three phases

Phase 1: Stimulus preparation

Phase 2: Data collection

Phase 3: Acoustic and articulatory analysis

3.4.1. Phase 1: *Stimulus Preparation*

The study investigated two aspects of speech production in children using CI (i.e. acoustic and articulatory characteristics). Stimuli for acoustic analysis was prepared and validated as part of the present study depending on the acoustic parameters investigated. Malayalam Diagnostic Articulation Test-Revised (MAT-R, Neenu et al., 2011) was used as the stimuli for studying the articulatory characteristics.

3.4.1.1. Stimulus Preparation for Acoustic Analysis.

A total of 10 vowels and 19 consonants (nine stops, two fricatives, three affricates, six nasals) were selected for acoustic analysis. The selection of the target phonemes was based on the literature review and age of acquisition of phonemes in

Malayalam language (Neenu et al., 2011). Simple meaningful bisyllabic Malayalam words including the target phonemes in different word positions (initial/medial) were listed based on the parameters to be analyzed. Suitable words from Malayalam Diagnostic Articulation Test-Revised (MAT-R, Neenu et al., 2011) were also selected (including few words with clusters e.g. doctor). Phonemes which are less frequent in the conversational speech of Malayalam (e.g. /f/, /h/) and aspirated stops (Sreedevi & Irfana, 2013) were not considered as target phonemes.

3.4.1.2. Stimulus Rating.

The words were subjected to familiarity rating by three experienced speech-language pathologists (SLPs with more than three years of clinical experience) on a three-point rating scale (0-not familiar, 1-familiar, 2-very familiar). Words which were rated as familiar and very familiar by at least two out of three SLPs were chosen. Further, three culturally appropriate color pictures for each word were selected from the internet. The target pictures, along with orthographic representation were numbered and arranged on a single slide using Microsoft power point 2007. The picture stimuli prepared was rated for acceptability by three SLPs on a 3–point rating scale for familiarity, clarity, ambiguity, iconicity, and naturalness. The stimuli which were rated as acceptable (score of 1) and most acceptable (score of 2) by at least two out of three SLPs were chosen as the stimuli for acoustic analysis. Thus a total of 32 words including 10 VCV and 22 CVCV words were finalized as the stimuli for acoustic analysis. The target word list used for acoustic analysis is provided in Appendix B and the picture stimuli of the same is in Appendix C.

3.4.1.3. Stimuli for Articulatory Analysis.

Test Material: Malayalam Articulation Test-Revised (MAT-R, Neenu et al., 2011) was administered based on the chronological age of the participants for articulatory analysis. MAT-R is a single word articulation test developed to assess the acquisition of speech sounds in Malayalam for children in the age range of 3-6 years. The test consists of 100 target words for testing 10 vowels, 35 singleton consonants, and 30 consonant clusters. As MAT-R tests for vowels only in word-initial position, words were listed under respective vowels (/a/, /i/, /u/, /e/, /o/, /ə/) separately for initial, medial and final positions to obtain position-specific vowel errors. Consonants were tested in initial, medial and final positions based on its occurrence in Malayalam. Consonant clusters were tested in the initial and medial positions (15 each). The number of phonemes and consonant clusters tested in initial, medial and final positions are shown in Table 3.2. Picture stimuli of the words were used for response elicitation.

Table 3.2

Number of Vowels, Consonants and Consonant Clusters Tested in Initial, Medial and Final Positions according to MAT-R

Category of speech sounds	Initial	Medial	Final
Vowels	10	-	-
Consonants	25	30	5
Consonant clusters	15	15	-

3.4.2. Phase 2: Data Collection

3.4.2.1. Procedure.

The participants were tested individually in a quiet room with minimum environmental noise, seated comfortably next to the investigator. The recordings of the clinical group were made in sound-treated audiological testing rooms in the speech and hearing clinic or hospital, and that of the control group were made in a quiet room in a school or home. The parents of all children involved had given written informed consent prior to the data recordings. The cochlear implants of all participants were checked for functioning prior to participations using Ling six sound test. Participants were required to imitate the Ling 6 sounds /a/, /i/, /u/, /ʃ/, /s/, and /m/ prior to the data recording to check for hearing capabilities within the range of speech (Ling, 2002).

The stimuli for acoustic and articulatory analyses were presented using Microsoft PowerPoint 2007 against a white background, loaded on a 15-inch laptop screen (Lenovo G560). The pictures were presented one after the other for five seconds with an inter-stimulus interval of approximately 3 seconds. The words for acoustic analyses were presented three times in random order, and those in the articulation test were presented once. Before initiating the test, the participants were orally instructed as follows: “Name the picture shown to you on the computer screen”. The researcher provided three levels of verbal prompts to elicit the target words that were applied in a specific order, beginning with a prompt for a spontaneous production (e.g., a command to name the picture), progressing to a semantic cue of the target word if the child did not know it, and finally providing a direct imitation prompt if required, to obtain the response.

For acoustic analyses, a total of 96 words (32 words x 3 presentations) were elicited from each participant. For articulatory analyses, the number of words ranged between 43 and 100, depending on the chronological age of the participants. For e.g., if the chronological age of a child is five years, a total of 69 words were elicited. Verbal and token reinforcements were given for desired responses. A total of 7680 words (80 participants x 32 words x 3 repetitions) were elicited from the participants for acoustic analyses. The average time required for recording of CI group was 2.5 hours (with breaks when required) and 30-40 minutes for TDC. Time taken for data editing and analysis was approximately 8 hours for each participant.

3.4.2.2. Instrumentation.

The participants’ responses were recorded using Olympus multi-track linear PCM audio recorder (Model No: LS 100). The recorder was kept 10 cm away from the mouth of the participant.

3.4.3. Phase 3: Data Analyses

3.4.3.1. Acoustic Analyses.

The recorded speech samples were transferred onto a personal computer for analysis. The recorded target words were subjected to spectrographic inspection by three SLPs (including the researcher) who were native proficient speakers of Malayalam and experienced in the acoustic analysis of speech. They were asked to listen carefully and spectrographically inspect all the three uttered target words. The trials in which the words were best articulated with a clear spectrogram as rated by at least two out of three SLPs were selected for acoustic analysis. The selected samples were analyzed using Praat software, Version 5.1.27 (Boersma & Weenink, 2010) at a sampling frequency of 44.1 kHz. The samples were displayed using a broadband spectrogram with a pre-emphasis factor of '0.80'; the size and bandwidth were fixed to 100 points, and 160 Hz hamming window was used. The temporal and spectral parameters considered for the target phonemes in the study are depicted in Table 3.3.

Table 3.3

Temporal and Spectral Parameters Considered for the Target Phonemes

	Sl. No	Parameters	Position of target Phoneme	Target phonemes
Temporal parameters	1.	Vowel duration	Word initial position (VCV)	/a/,/i/, /u/, /e/, /o/, /a:/, /i:/, /u:/, /e:/, /o:/
	2.	Ratio of duration of long and short vowels	Word initial position (V:CV, VCV)	/a,a:/, /i,i:/, /u,u:/, /e,e:/, /o,o:/
	3.	Voice onset time	Word initial position (CVCV)	/p/, /b/,/t/,/d/, /ʈ/, /ɖ/, /k/, /ɡ/
	4.	Burst duration	Word initial position (CVCV)	/p/, /b/,/t/,/d/, /ʈ/, /ɖ/, /k/, /ɡ/
	5.	Closure duration	Word medial position (CVCV)	/p/, /b/, /r̠/, /t/,/d/, /ʈ/, /ɖ/, /k/, /ɡ/
	6.	Frication duration	Word initial position (CVCV)	/s/, /ʃ/, /ʂ/
	7.	Affrication duration	Word initial position (CVCV)	/c/, /ɟ/
	8.	Nasal consonant duration	Word medial position (CVCV)	/m/, /n/, /n̪/, /ɳ/, /ɲ/, /ŋ/
	9.	Word duration	Total duration of words with VCV word shape	/a/,/i/, /u/, /e/, /o/, /a:/, /i:/, /u:/, /e:/, /o:/
Spectral parameters	1.	Fundamental frequency	Phonation	/a/
	2.	Formant frequency (F_1, F_2)	Word initial position (VCV)	/a/,/ i/, /u/, /e/, /o/
	3.	Vowel Space Area (VSA)	Computed using F_1 and F_2 values	/a/,/ i/, /u/
	4.	Nasal murmur	Word initial position (CVCV)	/m/, /n/, /ɲ/

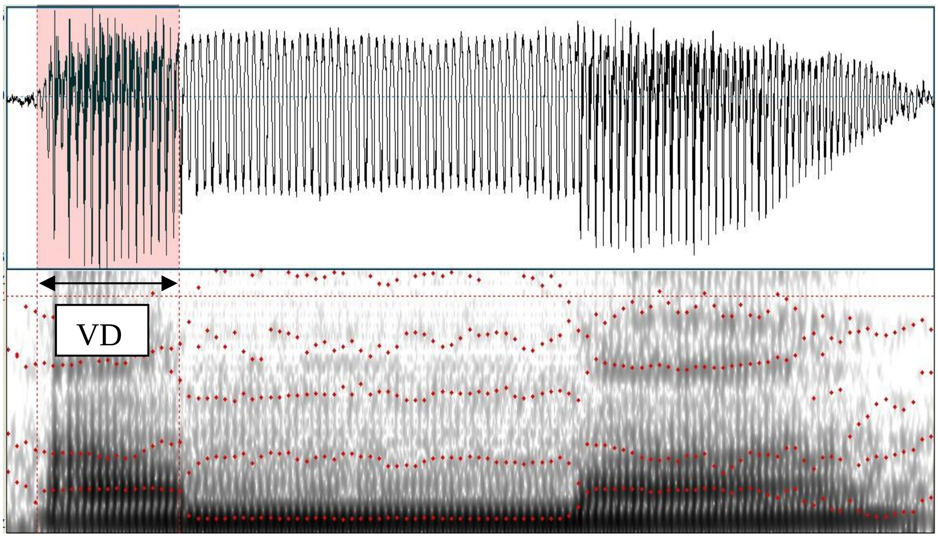
3.4.3.1.1. Temporal Parameters.

The temporal parameters considered for acoustic analysis were measured from the waveform with wideband bar type spectrogram as the reference. The temporal parameters were extracted as follows.

1. Vowel Duration (VD): VD is the time difference between the onset and offset of the vowel. On the waveform, vowel onset was determined by the first steady visible pulse of the steady formant structure characteristic of the vowel. Vowel offset was determined similarly by the last steady visible pulse of the waveform. VD was measured in the word initial position (VCV). Figure 3.1 illustrates the measurement of VD.

Figure 3.1

Waveform Showing VD of /a/ in the Word /amma/



2. Ratio of Duration of Long and Short vowels: It is measured as the ratio of the durations of long and short vowels.

$$\text{Ratio} = \frac{\text{Duration of long vowel}}{\text{Duration of short vowel}}$$

3. Voice Onset Time (VOT): VOT is the time duration between the articulatory release and the onset of voicing. On the waveform, VOT for unvoiced stops was measured as the interval between articulatory release and onset of voicing, whereas, voiced stop was measured as the interval between the burst of noise signaling articulatory release to the onset of voicing. Figure 3.2 and 3.3 illustrates the measurement of VOT in voiced and unvoiced plosives respectively.

Figure 3.2

Waveform Showing lead VOT of /b/ in the Word /ba:gə/

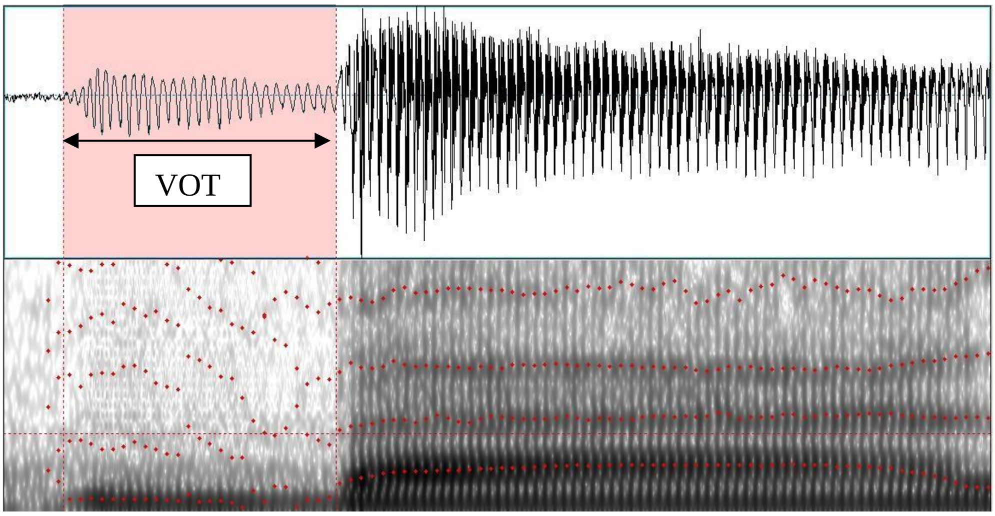
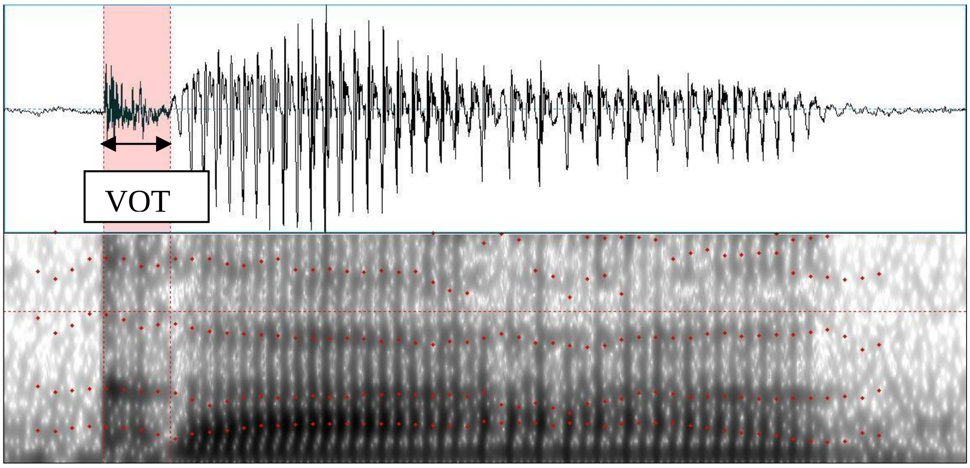


Figure 3.3

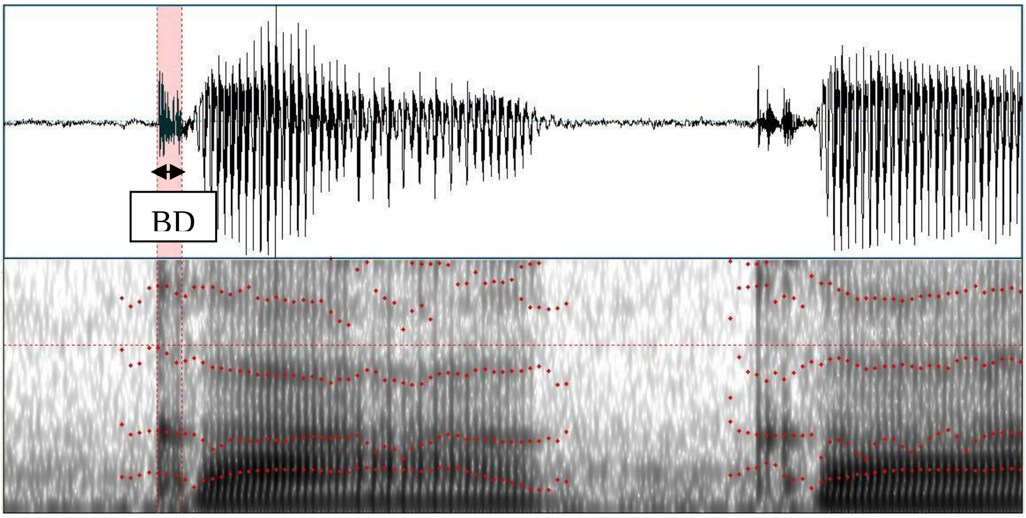
Waveform Showing lag VOT of /k/ in the Word /ka:kka/



4. Burst Duration (BD): BD was measured as the time difference between the onset and offset of the articulatory release in the word-initial stop consonant. On the wideband waveform, the cursor was placed at the point of onset of the burst and offset of burst just before the following vowel. Figure 3.4 illustrates the measurement of BD.

Figure 3.4

Waveform Showing the Measurement of BD for /k/ in the Word /ka:kka/



5. Closure Duration (CD): CD is measured as the time difference between the onset of the closure and the articulatory release in the production of a word-medial stop. On the waveform, CD was measured as the time difference between the offset of voicing for the preceding vowel and onset of the burst for the target consonant. Figure 3.5 and 3.6 illustrates the measurement of CD in voiced and unvoiced plosives, respectively.

Figure 3.5

Waveform Showing the Measurement of CD for /g/ in the Word /ba:gə/

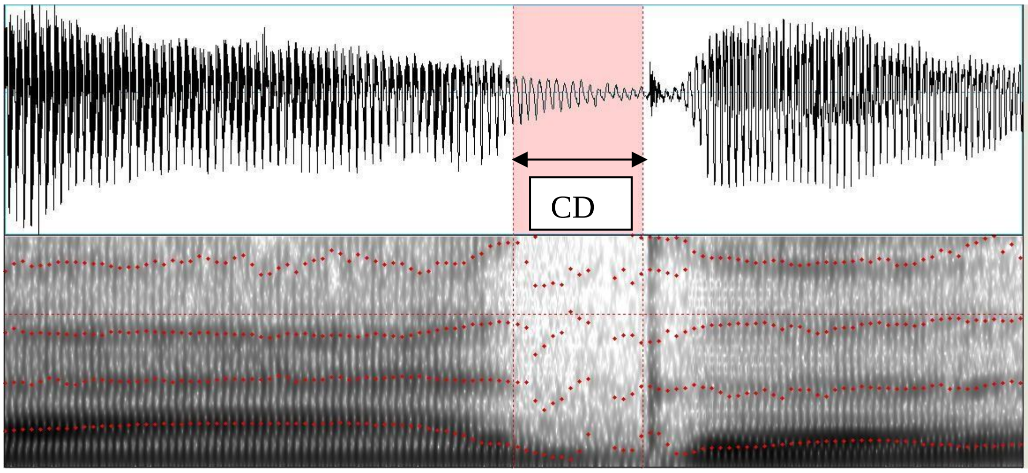
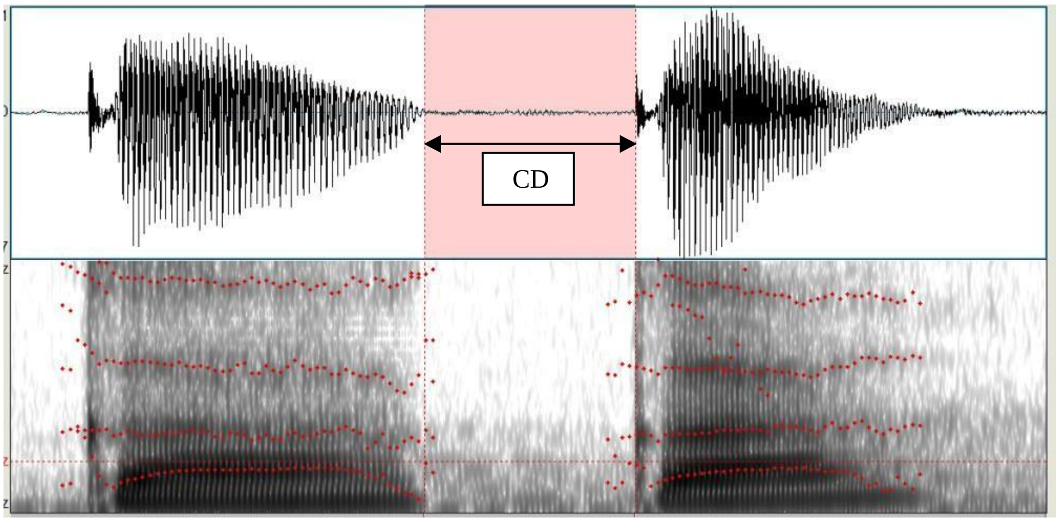


Figure 3.6

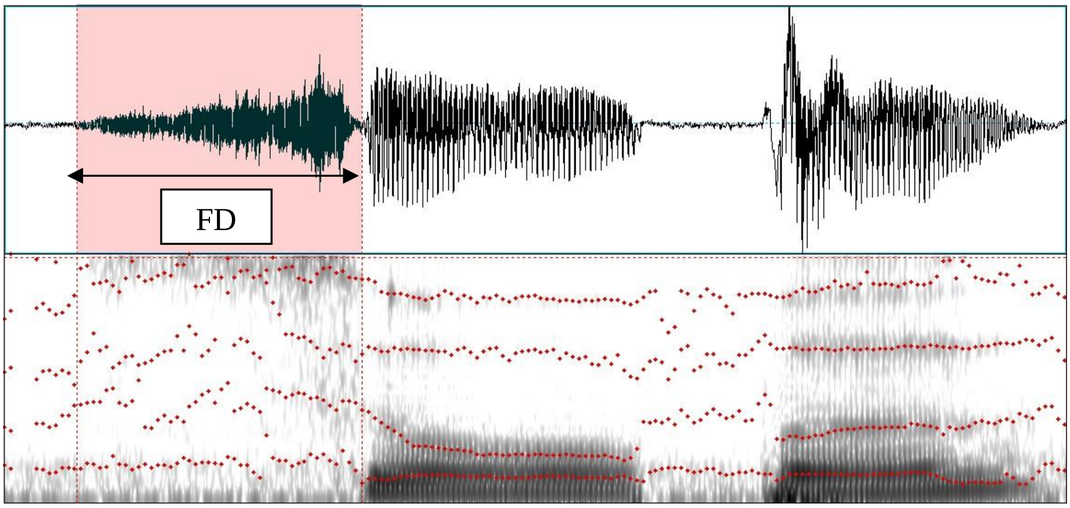
Waveform Showing the Measurement of CD for /k/ in the Word /ka:kka/.



6. Frication Duration (FD): FD is the time difference between the onset and offset of frication in the word-initial position. On the waveform, FD was measured by placing the cursor at the onset and offset of the frication till the onset of the following vowel. Figure 3.7 illustrates the measurement of FD.

Figure 3.7

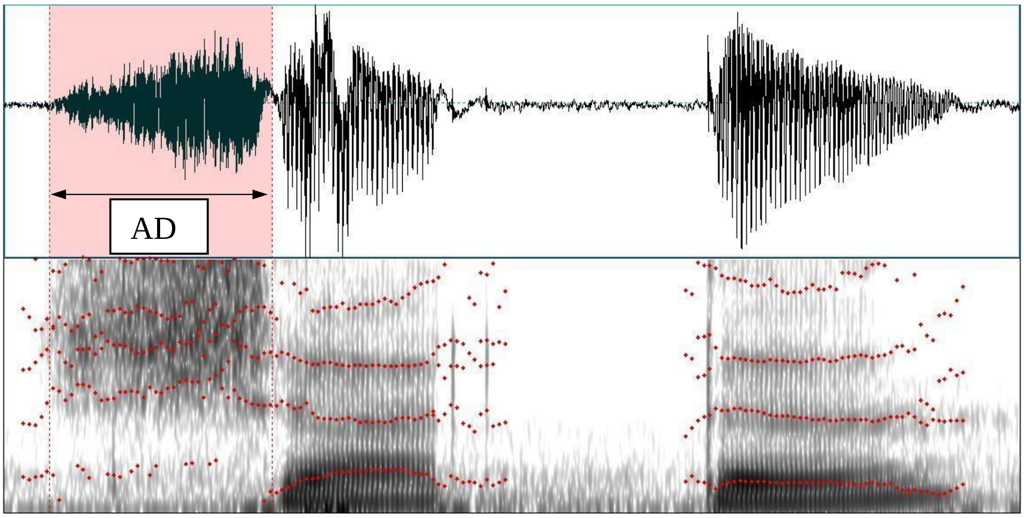
Waveform Showing the Measurement of FD for /s/ in the Word /so:ppə/.



7. Affrication Duration (AD): AD is the time difference between the onset and offset of the affrication in word-initial position. On the waveform, AD was measured by placing the cursor at the onset and offset of the affrication till the onset of the following vowel. Figure 3.8 illustrates the measurement of AD.

Figure 3.8

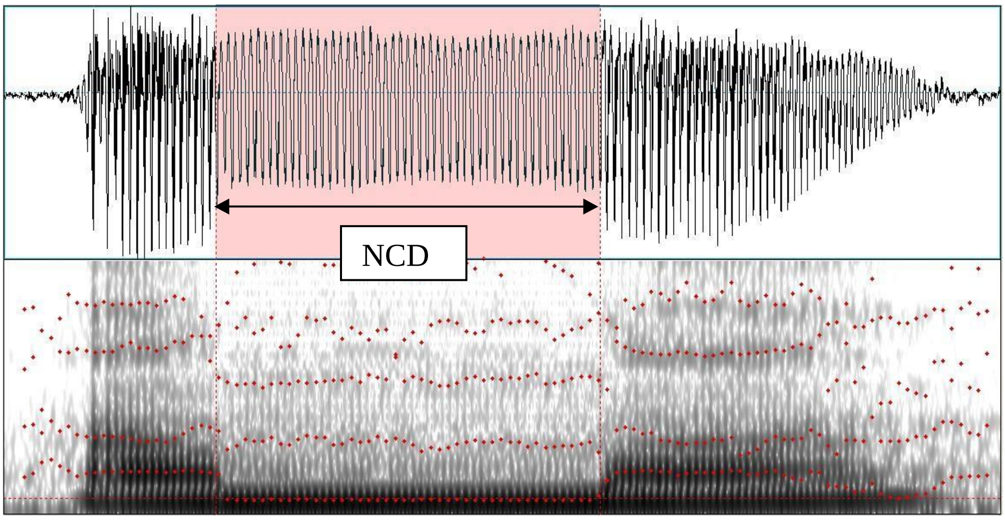
Waveform Showing the Measurement of AD for /ʂ/ in the Word /ʂarʈə/.



8. Nasal Consonant Duration (NCD): NCD is the time difference between the onset and offset of the nasal consonant in the word medial position. On the waveform, NCD was measured by placing the cursor at the onset and offset of the nasal consonant till the onset of the following vowel. Figure 3.9 illustrates the measurement of NCD.

Figure 3.9

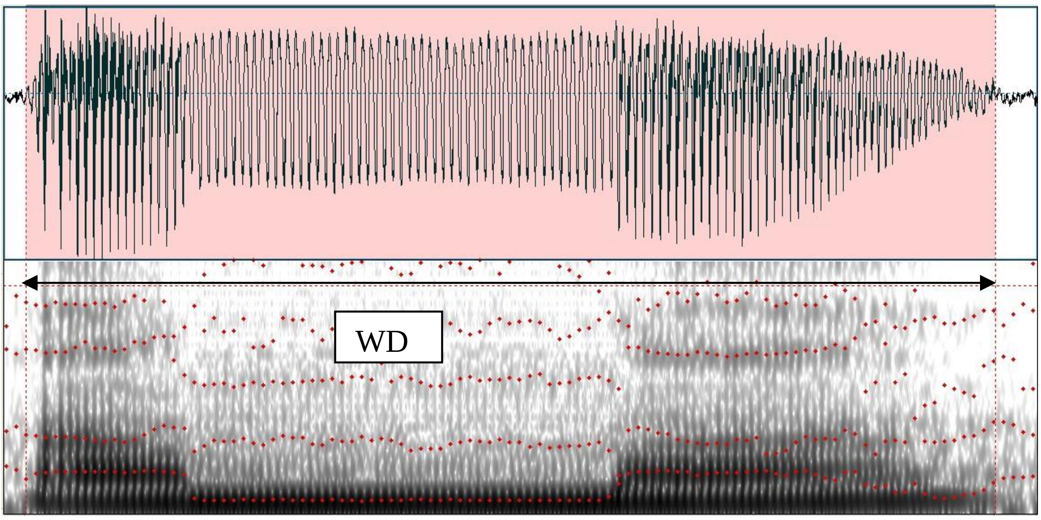
Waveform Showing the Measurement of NCD for /m/ in the Word /amma/



9. Word Duration (WD): WD is the time difference between the onset and offset of the target word. WD was measured by placing the cursor on the onset and offset of the target word on the waveform. It was analyzed for the words with VCV word shape. Figure 3.10 illustrates the measurement of WD. Durations were measured regardless of any sound substitutions and/or omissions in the intended monosyllabic words (Uchanski & Geers, 2003).

Figure 3.10

Waveform Showing WD of the Word /amma/

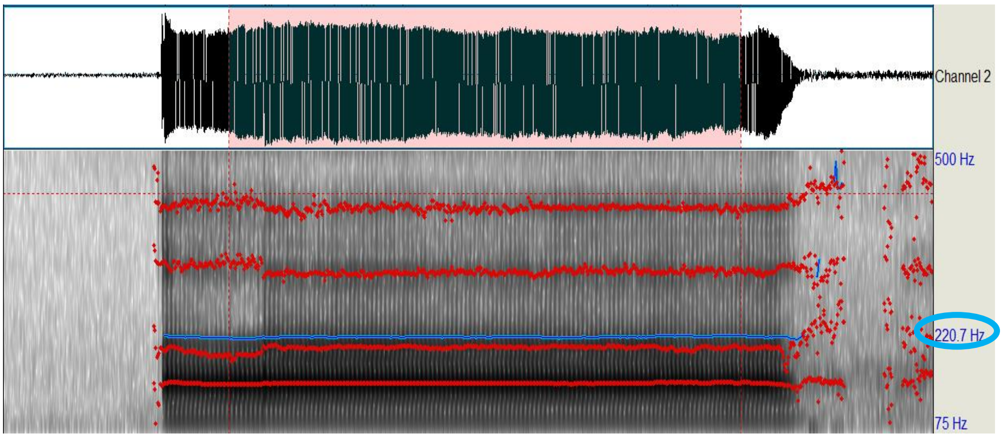


3.4.3.1.2. Spectral Parameters.

1. Fundamental Frequency: It is the frequency most often used by a person while speaking. A three-second segment with stable pitch was considered for visual estimation of pitch. The cursor was placed on the pitch line (depicted in blue color) in the spectrogram, and the frequency value shown for the selected point was considered. Figure 3.11 illustrates the measurement of habitual frequency.

Figure 3.11

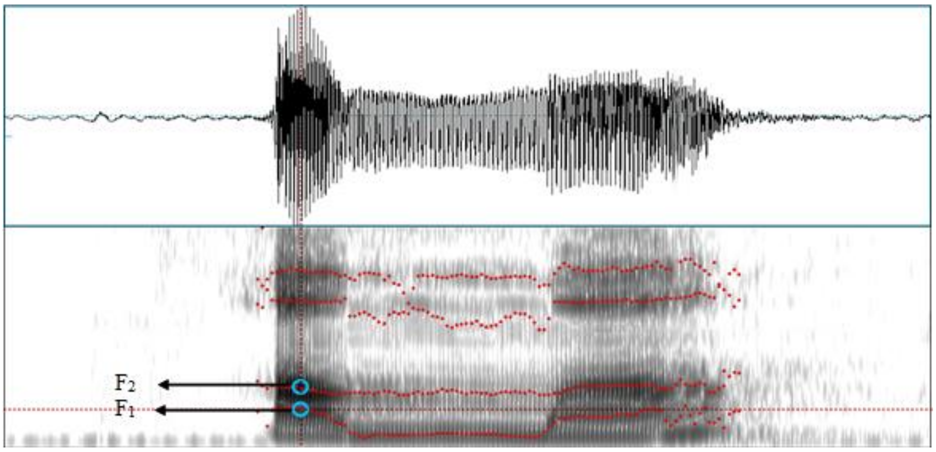
Illustration of Measurement of the Fundamental Frequency of /a/



2. Formant Frequency (F_1, F_2): Formants are the frequency peaks in the spectrum of a vowel with a higher degree of energy (F_1, F_2). The frequency of first (F_1) and second (F_2) formants for each target vowel was measured at the midpoint of the vowel. Figure 3.12 illustrates the measurement of formant frequencies.

Figure 3.12

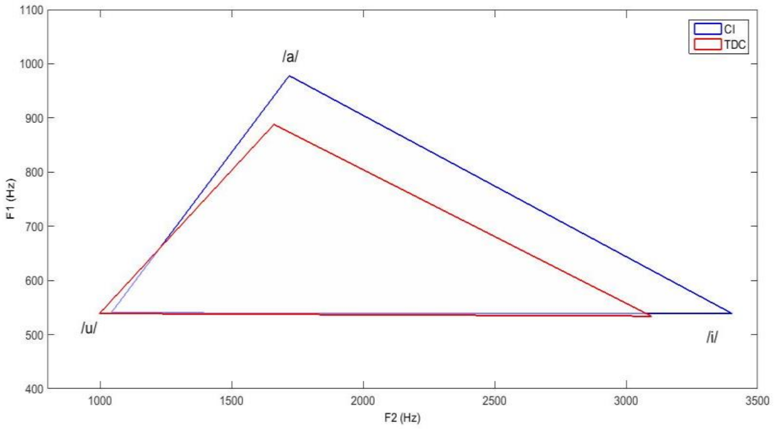
Illustration of Measurement of Formant Frequencies (F_1, F_2 of /a/) for the Word /amma/



3. Vowel Space Area (VSA): VSA was calculated for low central vowel /a/, high front vowel /i/ and high back vowel /u/. The formant frequency values were entered in a MATLAB (7.9.0.529) based program in order to obtain the vowel triangle and VSA. The frequency of the second formant (F_2) was plotted on the X-axis and the frequency of the first formant (F_1) on the Y-axis. This custom made program could plot two vowel triangles and calculate the area of the same. For obtaining the vowel triangle, the formant values (F_1 and F_2) were fed into the MATLAB based program, i.e. six formant frequency values per triangle (F_1 and F_2 of /a/, /i/ and /u/). Once the values were fed, two overlapping triangles were obtained. The triangles are color-coded for ease of comparison. Figure 3.13 shows a sample of vowel triangles obtained.

Figure 3.13

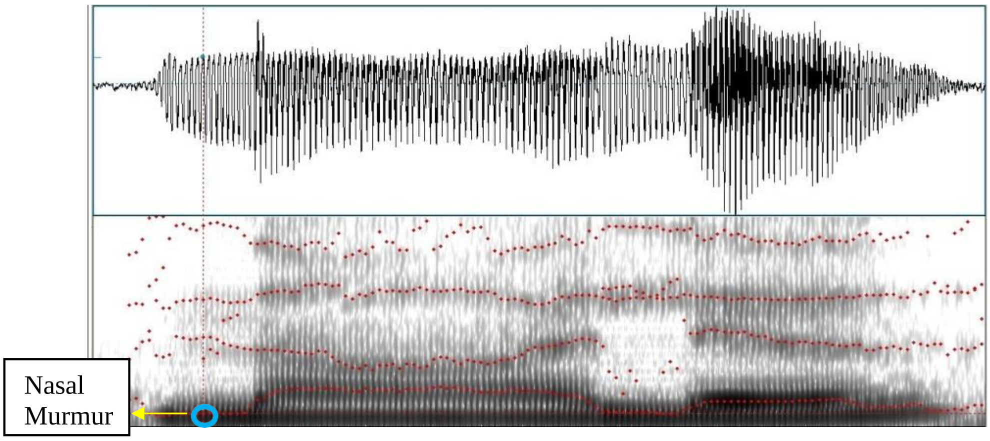
Depiction of Vowel Triangles Obtained



4. Nasal Murmur: Nasal formant or nasal murmur is a dominant low frequency resonance around 500 Hz. Nasal murmur was analyzed for the nasal consonants in the word-initial position. On the wide-band spectrogram, nasal murmur was measured by placing the cursor at the midpoint of the nasal consonant. Figure 3.14 illustrates the measurement of nasal murmur.

Figure 3.14

Illustration of Measurement of Nasal Murmur of the Word /ma:ŋa/



3.4.3.2. Articulatory Analysis.

The audio recorded samples were loaded onto a personal computer for analysis. Sony MDR-XB450 headphone was used for auditory- perceptual analysis. The investigator listened to the samples and transcribed the responses phoneme by phoneme using the Malayalam phonetic chart (Kavya Manohar, 2020) provided in Appendix D. Scoring sheet used for transcription is provided in Appendix E. Vowels, singleton consonants and consonant clusters were subjected to quantitative and qualitative analysis. The details of articulatory analysis procedures are provided under respective sections. Summary of articulatory measures are depicted in Figure 3.15.

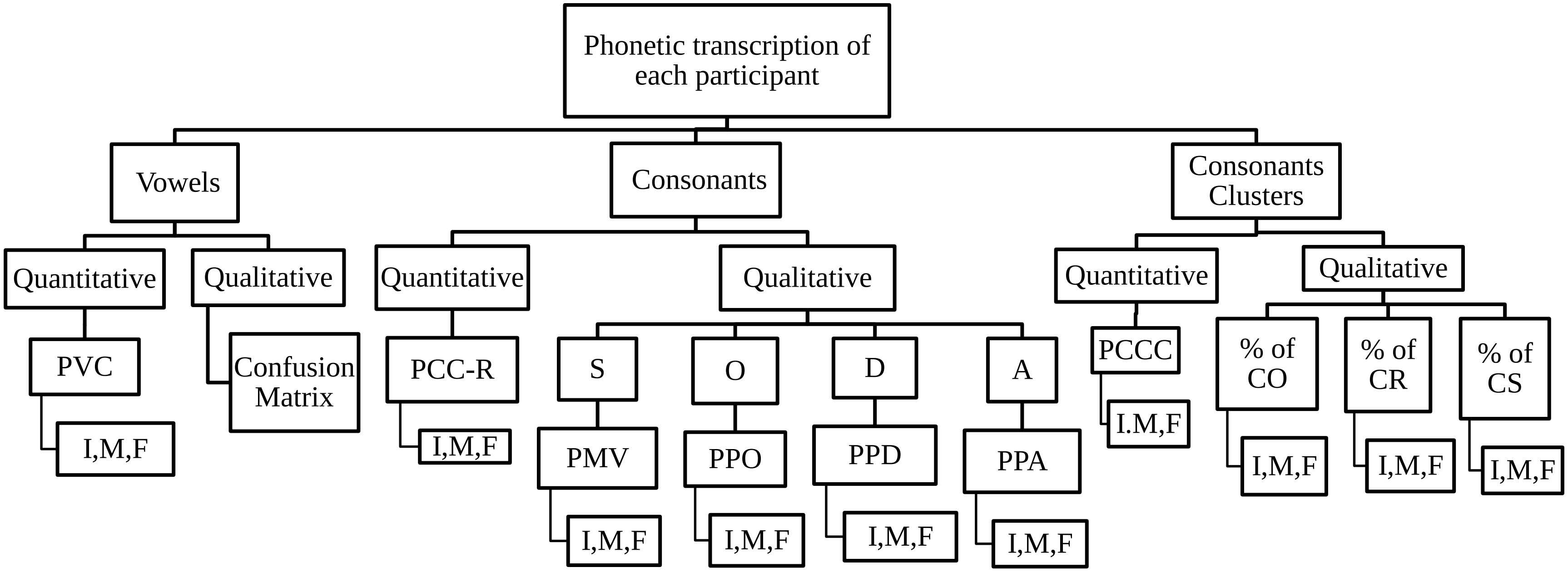
3.4.3.2.1. Vowels.

The analysis was carried out for 6 vowels (/a/, /i/, /u/, /e/, /o/, /ə/) in initial, medial, and final positions. As MAT-R tests for vowels only in word-initial position, other words in the test were also considered. Words were listed under respective vowels separately for initial, medial and final positions to obtain position-specific vowel error patterns. Number of target words for each vowel varied in different phoneme positions based on the frequency of occurrence in the test and also according to the chronological age of participants. Vowels were analyzed and profiled quantitatively and qualitatively.

a. Quantitative Analyses: Quantitative analyses included percentage of vowels correct (PVC; Shriberg, 1993) and percentage of substitution, omission, distortion and addition errors. To calculate PVC, the correct production of the intended vowels only was considered and production of other phonemes in the word was ignored while scoring the correctness of target vowels.

Figure 3.15

Flowchart of Articulatory Analysis



Note. PVC-Percentage of vowels correct, PCC-R- Percentage of consonants correct-revised, PCCC-percentage of consonant cluster correct, S-Substitution, O-Omission, D-Distortion,-A-Addition, PMV-Place, Manner, Voicing analysis, PPO/D/A-Percentage of participants with omission/distortion/addition errors, CO-Cluster omission, CR-Cluster reduction, CS- Cluster simplification, I, M,F- Initial, medial, final

Vowels produced correctly were scored ‘1’ and error productions were scored ‘0’. Any substitution, omission, distortion or addition of vowels was considered as incorrect. Examples for each error type seen are given below

- Substitution: /mu:tiram/ for /mo:tiram/, /o:/ is substituted by /u:/.
- Omission: /alama:r/ for /alama:ra/, where the vowel /a/ in final position is omitted.
- Distortion: In vowel distortions, the target vowel was pronounced as a non-Malayalam sound.
- Addition: /konnə/ for /onnə/, consonant /k/ is added in initial position.

The formula for calculating PVC is as shown below,

$$\textit{Percentage of vowels correct} = \frac{\textit{No. of vowels correct}}{\textit{No. of correct vowels + No. of incorrect vowels}} \times 100$$

Formula for calculating the percentage of substitution, omission, distortion and addition errors are as shown below.

$$\textit{Percentage of vowel S/O/D/A errors} = \frac{\textit{No. of vowel S/O/D/A errors}}{\textit{No. of correct vowels + No. of incorrect vowels}} \times 100$$

b. Qualitative Analyses: Detailed qualitative analysis of substitution errors of vowels was carried out to identify the substitution patterns. A confusion matrix was constructed, including the percentage of correct productions and substitutions with other vowels, as shown in Table 3.4. Value shown in bold indicates the percentage of correct production of the vowel in the corresponding row and other values in the row indicates the percentage the target vowel was substituted with the vowel in the respective column. For example, in the first row, value given in bold (97.36) indicates the percentage of correct production of /a/ and value under in the column /i/ (0.18) indicates the percentage of times /a/ was substituted with /i/.

Table 3.4

Example for Confusion Matrix of Vowel Substitution Errors

		Vowel produced					
		/a/	/i/	/u/	/e/	/o/	/ə/
Target vowel	/a/	**97.36**	0.18	-	0.28	0.38	1.80
	/i/	-	**96.92**	-	1.95	-	1.13
	/u/	-	3.83	**91.33**	-	-	4.84
	/e/	0.67	3.33	2.00	**92.67**	-	1.33
	/o/	3.97	-	6.70	-	**89.33**	-
	/ə/	1.41	-	-	-	-	**98.59**

Note. Percentage of correct productions is in bold

3.4.3.2.2. Consonants.

MAT-R tests for 35 consonants in initial position, 30 consonants in medial position and 5 consonants in final position. In the present study, number of consonants tested varied according to the chronological age of participants. Consonant productions were subjected to detailed quantitative and qualitative analyses. Percentage of consonants correct-revised (PCC-R) was calculated for quantitative analysis. SODA (Substitution, omission, distortion & addition) and PMV (Place, manner & voicing) analysis was employed for understanding error patterns (qualitative analysis).

a. Quantitative Analyses.

For quantitative analysis, consonants were listed under various places and manners of articulation and phoneme positions from the entire list of words in MAT-R. In MAT-R, each target phoneme in a particular position is tested only once in a single word. In the present study each target phoneme was assessed in all words/positions wherever it occurred in the list of words in MAT-R. For example,

/kuɖa/ is the target word for /k/ in initial position. For quantitative analysis the word was also considered for /ɖ/ in medial position. Similarly, the entire list of words were considered. This was done to increase the number of words for quantitative analysis and also to get a comprehensive impression of the child’s production in different linguistic contexts.

Percentage of consonants correct-revised (PCC-R, Shriberg, Austin, Lewis, Mc Sweeny, & Wilson, 1997) was calculated for various places and manners of articulation. Consonants produced correctly were scored ‘1’ and error productions were scored ‘0’. Any substitution, omission or addition of consonants was considered as errors. PCC-R for each consonant was calculated, and the overall PCC-R was estimated. PCC-R was calculated using the following equation.

$$PCC\text{-}R = \frac{\textit{No. of consonants correct}}{\textit{No. of correct consonants} + \textit{No. of incorrect consonants}} \times 100$$

An attempt was made to compare PCC scores across positions when there were a minimum of five target words per position. A criterion of minimum of five words was set because calculating percentage for numbers less than five possibly lead to erroneous representation of participants’ production. Among the eight places of articulation, data of velars and glottal phonemes were combined and represented together as there was only one phoneme with glottal place of articulation (/h/). Hence a total of seven places of articulation were considered for analysis which included bilabials, labiodentals, dentals, alveolars, retroflex, palatals, and velars and glottal. Phoneme position-wise analysis was not carried out for places of articulation due to disparity in the number of target words considered in each position. For e.g. number of words in the medial position for labiodentals and dentals were 'four' and that for velars was 'three'.

Manners of articulation tested included stops, nasals, fricatives, affricates, glides, laterals, trill, flap and approximant. Few of the manners with similar articulatory features were combined to meet the minimum target criteria (five words).Thus fricatives and affricates were combined as they have a common articulatory feature of fricative release of air. Similarly, glides, laterals, trill, flap and approximants were combined as these phonemes fall under the category of approximants. Thus a total of four categories of manners of articulation were considered for analysis which included: stops, nasals, fricatives/affricates and approximants. PCC-R was computed in initial and medial positions for stops and fricatives and affricates. For nasals and approximants, it was calculated in final position also. The data were subjected to appropriate statistical analyses for within and between-group comparisons.

b. Qualitative Analyses.

For qualitative analysis, only one target word for each phoneme was considered as per the stimulus of MAT-R, unlike quantitative analysis. For example, the target word for velar stop /k/ in word-initial position was /kuɖa/. Consonant errors were grouped into substitution, omission, distortion and addition errors (SODA). Substitution errors were further subjected to place, manner and voicing (PMV) analysis to identify specific articulatory error patterns.

1. SODA Analysis

Participants’ error productions of singleton consonants were classified into substitutions, omissions, distortions and additions (SODA).

- Substitutions: Errors in which a target consonant was replaced by another sound E.g., “crow” /ta:tta/ for /ka:kka/, velar /k/ is substituted by dental /t/.

- Omissions: Errors in which a target consonant was not produced. E.g., “ant” /umbə/ for /uṛumbə/), /ṛ/ is omitted.
- Distortions: Errors in which a target consonant was unclear
- Additions were the errors in which an extra phoneme was added e.g., “ring” /mon̪tiram/ for /mo:tiram/, consonant /n̪/ is added.

The target phonemes were categorized under respective places and manner of articulation to identify error patterns specific to these categories. An attempt was made to represent the errors with respect to the phoneme position also. Percentage of correct production, substitution, omission, distortion and addition was calculated and expressed in terms of percentage of participants.

The formula for calculating percentage of participants with correct production is as shown below.

$$\textit{Percentage of participants with correct production} = \frac{\textit{No. of participants correctly producing the target consonants}}{\textit{Total no. of participants}} \times 100$$

The formula for calculating percentage of participants with substitution, omission, distortion and addition errors are as shown below.

$$\textit{Percentage of participants with S/O/D/A/ errors} = \frac{\textit{No. of participants with S/O/D/A errors}}{\textit{Total no. of participants}} \times 100$$

2. ***PMV (Place -Manner-Voicing) Analysis:***

The PMV analysis involves classifying substitution errors according to place, manner, and voicing characteristics to identify error patterns. In this analysis, only substitutions errors are considered. Distortions, omissions and additions are not explained by this method.

Procedure: Consonants were listed under various places and manners of articulation. Substitution errors of each phoneme were identified separately for various phoneme positions (initial, medial & final). The phoneme and the corresponding place of articulation with which a particular phoneme is substituted were profiled. The percentage of substitutions with a particular place was calculated. For e.g. If phoneme /g/ has four substitutions; 3 with /b/ (bilabial) and 1 with /t/ (dental), then 75% of the time /g/ is substituted with a bilabial and 25% with a dental. Further, the overall percentage of substitutions for each place of articulation (combining all phonemes of that POA) was calculated. Similarly, substitutions were subjected to manner error analysis.

Voicing Feature Analysis: Voicing feature was analyzed only for those phonemes with voiced-unvoiced cognates. Therefore, stops and affricates were only considered for this analysis. Percentage of participants who produced voicing feature correctly was calculated in word-initial and medial positions considering both correct productions and substitution errors. The correctness of place and manner features was not considered for this analysis. For e.g. if /g/ is substituted with /d/, then the production of voicing is correct even though there is error in place of articulation (velar with dental). Percentage of correct production of voicing feature was computed and tabulated for each phoneme.

3.4.3.2.3. Consonant Clusters.

MAT-R tests 30 clusters in initial and medial positions (15 each). Number of clusters tested varied according to the chronological age of participants. The older group of participants was tested for 15 clusters each in the initial and medial positions, whereas the younger group of participants had variable number of clusters. Cluster productions of participants were subjected to quantitative and qualitative analyses and the detailed procedure will be discussed under respective sections.

a. Quantitative Analysis.

For quantitative analysis, initial and medial clusters were further subdivided based on its constituent consonants. For example, in the initial position there were four clusters beginning with /s/ (C_1) followed by stop or lateral (C_2). So they were grouped together as clusters with fricatives for better representation of cluster production. Similarly, initial clusters were divided into clusters with trill, flap/glides and laterals. Medial clusters were divided into clusters with fricatives, trills/glides and nasals. Clusters included in initial and medial positions are shown in Table 3.5.

Table 3.5

Consonant Cluster Types Considered for Quantitative Analysis in Word Initial and Medial Positions

Position	Cluster type	Consonant Clusters
Initial clusters	With fricative	/sk-/, /st^{h-}/, /sp-/, /sl-/
	With laterals (/ɭ/)	/gɭ-/, /pɭ-/, /bɭ-/, /kɭ-/
	With trill, flap & glides (/ṛ/,/r/, /j/,/v/)	/tṛ-/, /bṛ-/, /pṛ-/,/kṛ-/, /gr-/, /kj-/, /ʃv-/
Medial clusters	With fricatives (/s/, /ʂ/)	/-sk-/, /-st-/,/-stṛ-/, /-kʂ-/
	With trills & glides (/ṛ/,/j/)	/-tṛ-/, /-kṛ-/, /-lj-/, /-dj-/
	Nasal clusters	/-nr̲-̲/, /-nt-/, /-nɟ-/, /-ɳɖ-/, /-ŋg-/, /-ndr-/, /-ndj-/

The percentage of consonant clusters correct (PCCC) was calculated for initial and medial clusters and its sub types for clinical and control groups.

Formula for calculating the same is as shown below

Percentage of consonant clusters correct =

$$\frac{\textit{No. of consonant clusters produced correctly}}{\textit{Total no. of consonant clusters tested}} \times 100$$

b. Qualitative Analyses.

For qualitative analysis, initial clusters are sub-grouped into clusters with fricatives, laterals, trills/ flaps, and glides. Medial clusters were classified into clusters with fricatives, laterals, trills/ flaps, nasals and cluster with /ʂ/. Clusters included in initial and medial positions are shown in Table 3.6.

Table 3.6

Consonant Cluster Types Considered for Qualitative Analysis in Word Initial and Medial Positions

Position	Cluster type	Consonant Clusters
Initial clusters	With fricatives	/sk-/, /st^h-/, /sp-/,/sl-/
	With laterals(/ɭ/)	/gɭ-/, /pɭ-/, /bɭ-/, /kɭ-/
	With trills and flaps (/ṛ/,/r/)	/tṛ-/, /bṛ-/, /pṛ-/,/kṛ-/, /gr-/
	With glides (/j/,/v/)	/kj-/, /ʃv-/
Medial clusters	With nasals	/-nr̲-̲/, /-nt-/, /-nɟ-/, /-ɳɖ-/, /-ŋg-/, /-ndr-/, /-ndj-/
	With laterals(/l/)	/-lj-/, /-dj-/
	With fricatives	/-sk-/, /-st-/,/-stṛ-/
	With trills and flaps (/ṛ/)	/-tṛ-/, /-kṛ-/
	/ʂ/ cluster	/-kʂ-/

Consonant cluster productions under each cluster type were classified into Greenlee's (1974) stages of cluster acquisition for good understanding of error patterns. This consists of 4 stages:

Stage 1: Deletion of entire cluster: Both constituents of the consonant cluster are deleted.

E.g. /pukkam/ for /pustakam/, /st/ is deleted.

Stage 2: Cluster reduction: Consonant cluster is reduced to a single consonant. This can be classified into C_1/C_2/C_3 deletion and coalescence errors.

- C_1 deletion: deletion of the first consonant (C_1) from the cluster and retaining the second consonant (C_2). E.g., /ku:ɭ/ for /sku:ɭ/, fricative /s/ (C_1) is deleted
- C_2 deletion: deletion of the second consonant (C_2) from the cluster and retaining the first consonant (C_1). E.g., /be:ɖ/ for /ble:ɖ/, lateral /l/ (C_2) is deleted.
- Coalescence: Reducing the target cluster to one consonant in which the features from both consonants of the target cluster is combined to a single consonant that differs from both consonants. E.g., /ca:maṛa/ for /kja:maṛa/

Stage 3: Cluster simplification: Both consonants of the cluster are produced, although both consonants are not always produced correctly. E.g., /gja:mam/ for /gra:mam/.

Stage 4: Correct production: Both consonants of the cluster are produced correctly.

The percentage of correct production and cluster error productions (CO-Cluster omission, CR- cluster reduction & CS-cluster simplification) was calculated for each cluster type. Formula for calculating the same is shown below.

$$\textit{Percentage of consonant clusters correct} = \frac{\textit{No. of consonant clusters produced correctly}}{\textit{Total no. of consonant clusters}} \times 100$$

$$\textit{Percentage of CO/CR/CS errors} = \frac{\textit{No. of CO/CR/CS errors}}{\textit{Total no. of clusters}} \times 100$$

3.5. Statistical Analysis

The obtained data was tabulated and subjected for appropriate statistical analysis using SPSS (Statistical Package for Social Sciences) version 21. All the obtained data was subjected to test of normality using Shapiro-Wilk’s test. Parametric tests were used for the data which followed normal distribution and non- parametric tests were run when normality was not established. Parametric tests included Independent t-test, MANOVA and Single sample t test. Non-parametric tests used included Kruskal- Wallis H test, Mann Whitney U test, Wilcoxon signed rank test. Cronbach’s alpha was also employed for intra-rater and inter-rater reliability for acoustic analysis. Cohen’s Kappa statistics was performed for intra-rater and inter-rater reliability for articulatory analysis.

3.6. Inter and Intra –Rater Reliability

For intra and inter-judge reliability 20% of the samples of children using CI and TDC were selected randomly. The investigator re-analyzed 20% of the speech samples from each group (clinical & control) within 4-weeks time interval. Inter-rater reliability of acoustic analysis was carried out by three experienced Speech-language pathologists who are native proficient speakers of Malayalam and had a minimum of 3 years of clinical and research experience in acoustic analysis of speech. Among the three judges, investigator also served as one of the judges. For articulatory analysis, inter-rater reliability was established using phoneme-by phoneme transcription by the judges. Correct productions were scored ‘1’ and incorrect responses were scored ‘0’ (nominal scale). Further, the scorings were statistically analyzed to establish point to point agreement for intra-rater and inter-rater reliability using Cohen’s kappa (k) coefficient.

The intra and inter-judge agreement was calculated for acoustic analysis in TDC. Cronbach's alpha score for intra and inter- judge reliability ranged from 0.86 to 0.96 and 0.83 to 0.93 respectively indicating good to excellent internal consistency. The intra and inter-judge agreement were calculated for acoustic analysis in children using CI. Cronbach's alpha score for intra-judge reliability ranged from 0.82 to 0.93, which indicates good to excellent agreement. For inter-judge reliability Cronbach’s alpha score ranged from 0.78 to 0.89 indicating good internal consistency across measurements.

The intra and inter-judge reliability for articulatory measures was assessed by Cohen's kappa coefficient for children using CI. The inter-judge reliability was found to be between 0.70-0.82, which indicates substantial to almost perfect agreement. Intra-judge reliability was found to be 0.88, which indicates almost perfect agreement.

Chapter 4: Results

The aim of the present study was to investigate the acoustic and articulatory characteristics of Malayalam speaking children using cochlear implant and to compare the same with typically developing children in the age range of 4 to 8 years.

The objectives of the study were

1. To investigate the acoustic (temporal & spectral) characteristics of speech across age groups (4.0-5.11 years & 6.0-7.11 years) in children using cochlear implants and typically developing children.
2. To compare the acoustic (temporal & spectral) characteristics of speech between children using cochlear implant and typically developing children.
3. To investigate the articulatory characteristics of speech across age groups (4.0- 5.11 years & 6.0-7.11 years) in children using cochlear implants.
4. To compare the articulatory characteristics of speech between children using CI and typically developing children.

A total of 80 Malayalam speaking children in the age range of 4 and 8 years were recruited for the study. Participants were divided into clinical and TDC. The clinical group consisted of 30 children (15 boys & 15 girls) with congenital hearing loss fitted with a multi- channel cochlear implant (CI) before the age of 3. The clinical group was further divided into two subgroups based on the number of years of cochlear implant use. Subgroup I consisted of participants with 2-3 years of cochlear implant experience (8 boys & 7 girls) and subgroup II with 3-4 years of implant experience (7 boys & 8 girls). The chronological age of subgroup I (2-3 years of CI experience) was in the range of 4.0-

5.11 years and subgroup II (3-4 years of CI experience) in the range of 6-7.11 years. A total of 50 age-matched typically developing children (TDC) were recruited. Similar to the clinical group, TDC group was further divided into two groups based on the chronological age of the participants (4.0-5.11 & 6-7.11 years).

The recorded speech samples of the participants were subjected to acoustic and articulatory analysis. The obtained results were tabulated and subjected to appropriate statistical analysis. The results of statistical analysis will be discussed under the following sections

- Acoustic characteristics of speech in children using CI and TDC
    - Temporal parameters
    - Spectral parameters
- Articulatory characteristics of speech in children using CI and TDC.
    - Quantitative analysis
    - Qualitative analysis

4.1. Acoustic Characteristics of Speech in Children using CI and TDC

The acoustic data was analyzed using Praat software (version 6.0.35) in order to obtain the temporal and spectral measures. Statistical analyses were carried out using SPSS (Statistical Package for Social Science) version 21. Normality of the data was tested using Shapiro Wilk's test of normality to determine the tests to be employed for inferential statistics. The findings revealed that data did not satisfy normal distribution principle ($p<0.05$). Most of the parameters did not have outliers, however remained non-normal. Hence, non-parametric tests were applied for further statistical comparisons.

Mann-Whitney U test was employed for between age group and across group comparisons. The primary focus of between age group comparisons in CI was to determine the changes in acoustic characteristics of speech with increase in the duration of implant experience (2-3 vs. 3-4 years of CI experience). Between age group comparison in TDC aimed at finding the age wise changes (4.0-5.11 years & 6-7.11 years) in the acoustic measures. Across group comparison was carried out to determine the significant difference in acoustic characteristics between age-matched groups of children using CI and TDC. Effect sizes were calculated using an equation to convert z-score into the effect size estimate ‘r’, $r = Z/\sqrt{N}$, in which Z is the z-score that SPSS produces and N is the number of total participants on which z is based (Field, 2009).

Gender wise comparisons were carried out using Mann -Whitney U test to determine the need for sub dividing the groups based on gender for further statistical comparisons. The findings revealed that more than 90% (69/76 variables) of the data did not show significant gender differences ($p>0.05$). Apart from this, there were missing values in the CI data owing to the misarticulations of phonemes. This resulted in further reduction in the number of participants among both boys and girls. Hence, gender was not considered for further statistical comparisons as these variables could lead to inconclusive results. A flowchart of the statistical analyses performed on acoustic measures of speech is depicted in Figure 4.1.

The acoustic characteristics investigated in the present study included nine temporal and four spectral parameters of different classes of phonemes such as vowels, stops, nasals, fricatives and affricates. Multiple acoustic measures were investigated for vowels and stops. Hence the results of temporal and spectral parameters will be represented under each phoneme class as shown in Figure 4.2 and 4.3 respectively. For multiple comparisons between age groups of CI and TDC and for between group comparisons (CI vs TDC), alpha correction was not applied (Feise, 2002).

Figure 4.1

Flowchart of the Statistical Analyses Performed on Acoustic Measures of Speech

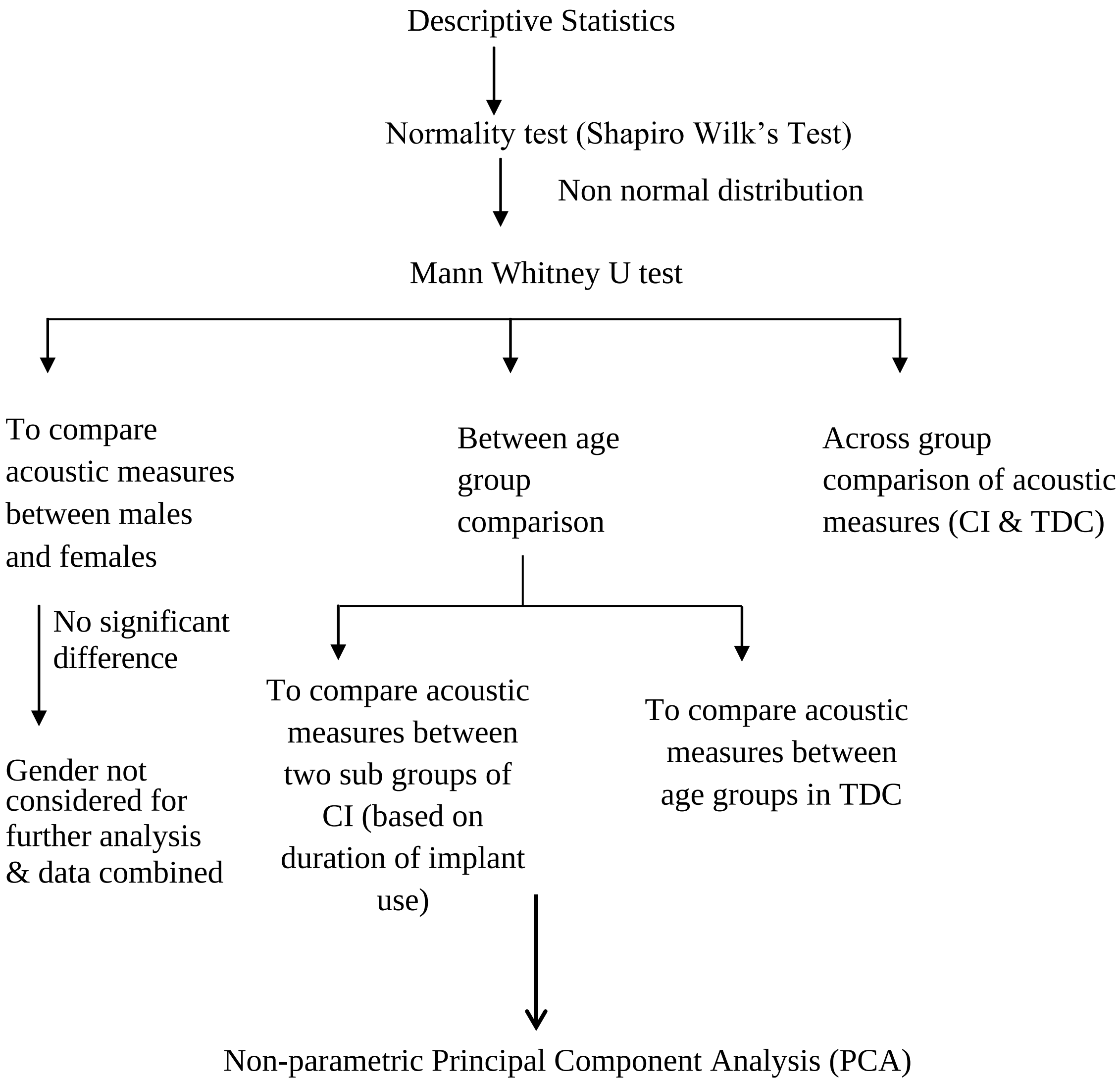


Figure 4.2

Temporal Parameters Investigated under each Phoneme Class

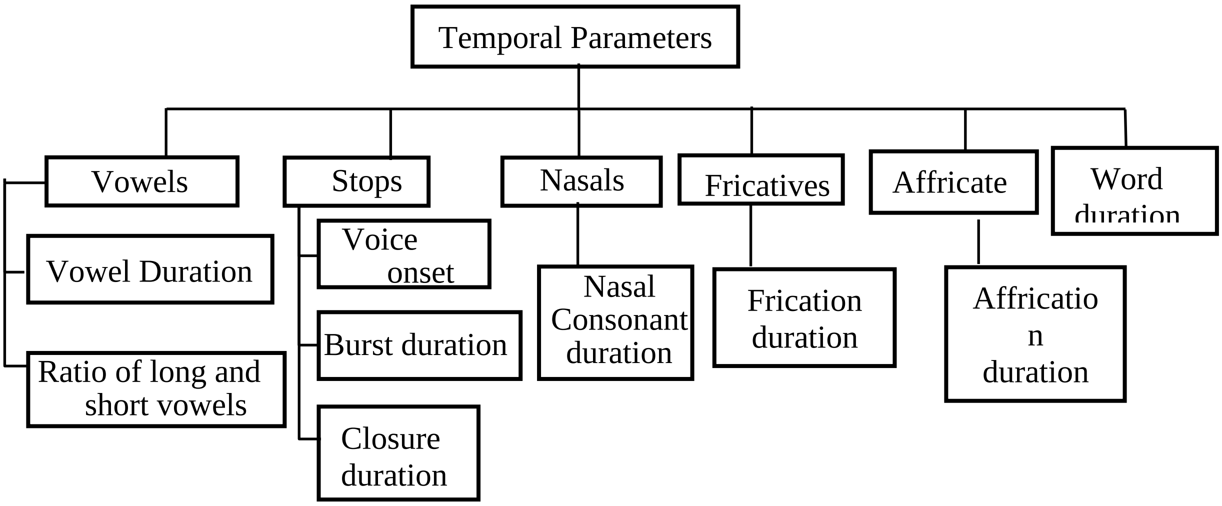
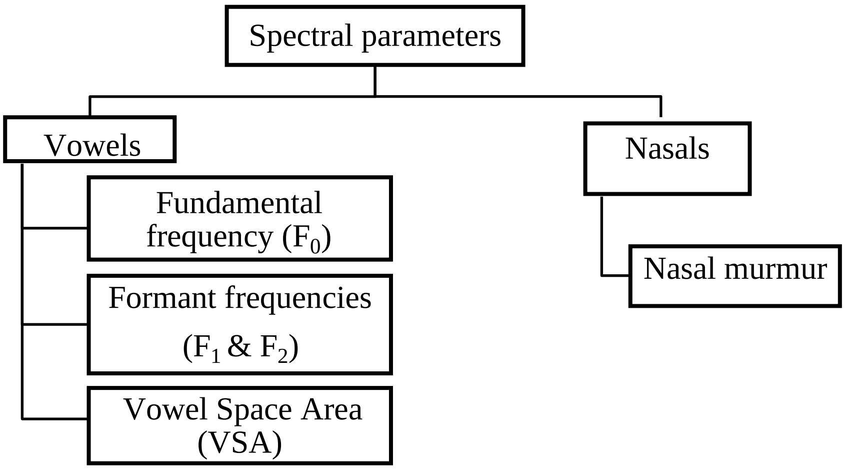


Figure 4.3

Spectral Parameters Investigated under each Phoneme Class



4.1.1. Temporal Parameters

For between age group comparisons of CI, the groups will be described in terms of duration of CI use i.e. 2-3 years (younger group) and 3-4 years (older group). For comparisons across CI and TDC, chronological age of the participants was considered.

4.1.1.1. Vowels.

The temporal measures of vowels consisted of vowel duration and ratio of duration of short and long vowels.

4.1.1.1.1. Vowel Duration.

Vowel duration (VD) was measured for 5 short vowels (/a/, /i/, /u/, /e/, /o/) and 5 long vowels (/a:/, /i:/, /u:/, /e:/, /o:/) in the word initial position. The mean, standard deviation, median and inter quartile range, |z|, *p* and *r* values of vowel duration in children using CI and TDC were measured and are provided in Table 4.1 and Table 4.2.

Table 4.1

Mean, Standard Deviation, Median, Inter Quartile Range, |z|, *p and r Values of Vowel Duration between Children with 2-3 and 3-4 years of CI Experience*

Vowel Duration	4.0-5.11y (2-3y of CI use)				6.0- 7.11y (3-4y of CI use)				|z|	*p*	*r*
	Mean	SD	Median	IQR	Mean	SD	Median	IQR			
/a/	144.25	38.17	146.88	45.99	137.62	29.43	142.12	40.03	1.43	0.15	0.26
/i/	179.43	48.48	193.19	73.47	196.81	59.73	212.36	127.29	0.89	0.37	0.16
/u/	134.96	27.87	131.81	90.08	134.78	60.64	138.28	122.56	0.23	0.82	0.04
/e/	211.12	53.42	219.13	97.62	209.83	37.24	218.61	46.51	0.56	0.58	0.10
/o/	170.63	39.95	183.97	72.10	165.91	47.24	164.17	100.99	0.23	0.82	0.04
/a:/	392.07	90.96	407.97	185.52	394.25	105.09	364.31	172.00	0.31	0.76	0.06
/i:/	321.65	105.6	280.61	100.33	297.93	105.19	279.00	216.83	0.73	0.46	0.13
/u:/	330.18	65.21	325.55	118.27	314.11	62.90	293.89	85.65	0.52	0.60	0.09
/e:/	473.78	80.82	459.85	75.01	409.52	97.31	422.38	167.37	1.64	0.10	0.30
/o:/	407.43	93.29	396.34	158.43	380.85	98.02	378.82	111.63	0.52	0.52	0.09

*Note.*SD: standard deviation, IQR: interquartile range, *r*: effect size, y: years

Table 4.2

Mean, Standard Deviation, Median, Inter Quartile Range, |z|, p and r Values of Vowel Duration between Age Groups in TDC

Vowel Duration	4.0- 6.11 years				6.0- 7.11 years						
	Mean	SD	Median	IQR	Mean	SD	Median	IQR	|z|	*p*	*r*
/a/	145.21	26.16	127.45	34.64	131.56	22.75	126.85	32.68	0.61	0.54	0.10
/i/	212.36	38.04	124.70	72.13	123.77	34.79	126.97	51.90	0.15	0.87	0.02
/u/	138.28	17.37	105.80	18.46	91.69	15.56	93.27	23.97	2.65	0.00**	0.42
/e/	218.61	35.39	167.63	44.48	154.02	30.27	152.14	52.74	1.25	0.21	0.20
/o/	164.17	25.48	128.13	42.08	121.34	22.76	115.11	32.88	1.02	0.30	0.16
/a:/	364.31	58.22	299.55	83.98	281.99	53.75	273.76	61.08	1.13	0.25	0.18
/i:/	279.00	41.31	240.47	49.45	220.40	44.97	216.65	64.75	0.03	0.96	0.00
/u:/	293.89	50.75	237.91	61.14	207.05	42.38	192.69	71.26	2.27	0.02*	0.36
/e:/	422.38	58.44	336.90	84.93	312.52	42.42	308.86	65.28	1.28	0.20	0.20
/o:/	378.82	52.16	299.03	47.32	275.13	43.76	268.52	69.77	1.73	0.08	0.27

Note. SD: standard deviation, IQR: interquartile range; *r*: effect size

*p<0.05, **p<0.01

Results of Mann Whitney U test for between age group comparison indicated a non-significant decrease in vowel duration with increase in duration of implant use for most of the vowels expect for /i/ and /u/ in children using CI. In TDC, VD decreased with age for most of the vowels with a significant decrease in duration noticed for vowels /u/ (|z|=2.65, p<0.01, *r*=0.42) and /u:/ (|z|=2.27, p<0.05, *r*=0.36) as shown in Table 4.2. On observation, mid front vowel /e/ and its longer counterpart was found to be the longest in both groups. The high back vowel /u/ was observed to be the shortest among the short vowels in both groups. The results of Mann Whitney U test for comparing vowel duration between the groups are provided in Table 4.3.

Table 4.3

Results of Mann Whitney U Test for Comparison of Vowel Duration between Children using CI and TDC in both Age Groups

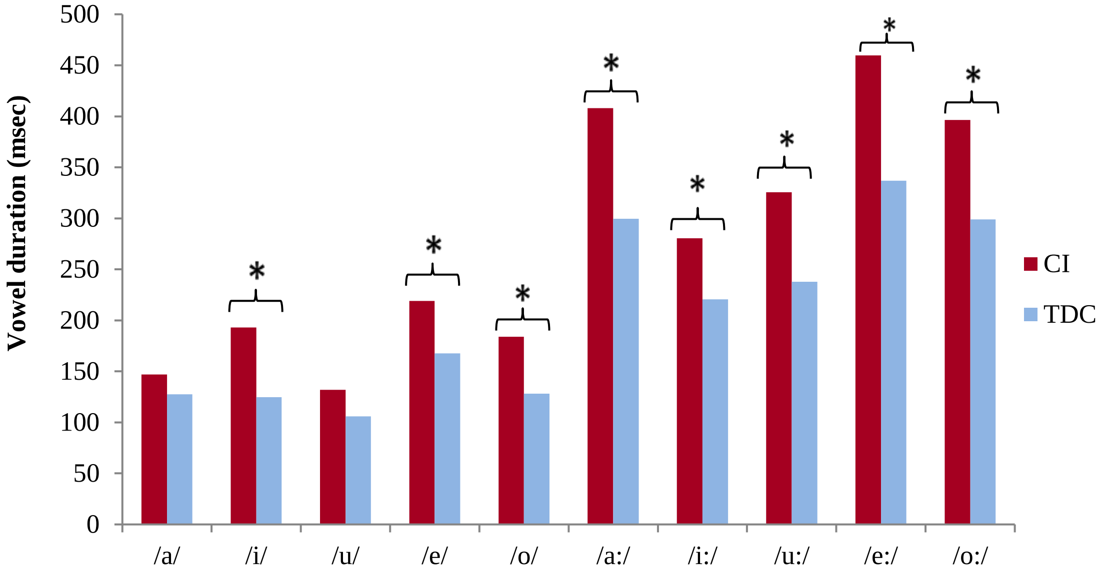
Vowel Duration	CI vs TDC (4.0-5.11 years)			CI vs TDC (6.0-7.11 years)		
	|z|	*p*	*r*	|z|	*p*	*r*
/a/	0.93	0.34	0.15	2.08	0.03*	0.33
/i/	3.42	0.00**	0.54	3.42	0.00**	0.54
/u/	1.71	0.08	0.27	1.88	0.06	0.30
/e/	2.64	0.00**	0.42	4.23	0.00**	0.67
/o/	3.08	0.00**	0.49	2.86	0.00**	0.45
/a:/	3.00	0.00**	0.47	3.42	0.00**	0.54
/i:/	3.87	0.00**	0.61	2.17	0.03*	0.34
/u:/	4.14	0.00**	0.65	4.65	0.00**	0.74
/e:/	4.48	0.00**	0.71	2.75	0.00**	0.43
/o:/	4.06	0.00**	0.64	3.56	0.00**	0.56

Note. *$p<0.05$, **$p<0.01$

The findings revealed that CI group had longer duration for all vowels compared to TDC. A significantly longer VD was manifested for all the vowels except short vowels /a/ and /u/ (p>0.05) in the younger CI group. When older age groups were compared, there was significantly longer VD for all short vowels except /u/ (p>0.05) and for all long vowels in children using CI. Overall it can be noted that irrespective of the duration of implant use, children using CI exhibited significant lengthening of vowels compared to TDC. Higher effect size (*r* value) was noted for long vowel /e:/, /u/: and /o:/ in younger group and for /u:/ and /e/ in older group The vowel durations of younger and older groups of children using CI and TDC are depicted in Figure 4.4 and 4.5 respectively. Figures are represented based on the median values.

Figure 4.4

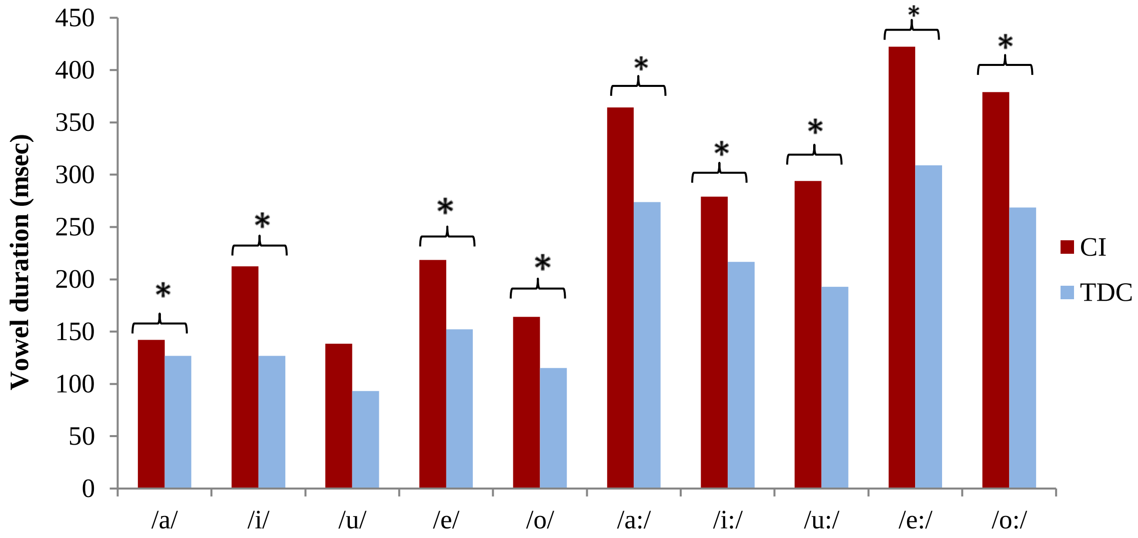
Vowel Duration of Children using CI and TDC in the Age Range of 4.0-5.11 years



Note. *p<0.05

Figure 4.5

Vowel Duration of Children using CI and TDC in the Age Range of 6.0-7.11 years



Note. *p<0.05

4.1.1.1.2. Ratio of Duration of Long and Short vowels.

Ratio of duration of long and short vowels in CI and TDC was computed. Mean, standard deviation, median and inter quartile range, |z|, *p* and *r* values of ratio of duration of long and short vowel in children using CI and TDC are provided in Table 4.4 and Table 4.5 respectively.

Table 4.4

Mean, Standard Deviation, Median, Inter Quartile Range, |z|, p and r Values of Ratio of Duration of Long and Short Vowels between 2-3 and 3-4 years of CI Experience

Ratio of vowels	4.0-5.11y (2-3y of CI use)				6.0-7.11y (3-4y of CI use)						
	Mean	SD	Median	IQR	Mean	SD	Median	IQR	|z|	*p*	*r*
/a/vs /a:/	3.04	1.17	2.84	0.77	2.70	0.76	2.61	0.93	0.52	0.60	0.09
/i/ vs /i:/	1.82	0.40	1.98	0.78	1.50	0.29	1.70	0.47	0.34	0.73	0.06
/u/ vs/u:/	2.80	1.38	2.44	2.30	2.78	1.39	2.29	2.84	0.18	0.86	0.03
/e/ vs /e:/	2.56	1.13	2.28	1.41	2.07	0.59	2.18	0.95	1.02	0.31	0.19
/o/ vs /o:/	2.81	0.93	2.97	1.60	2.90	1.15	2.91	1.91	0.02	0.98	0.00

Note. SD: standard deviation, IQR: interquartile range, *r*: effect size, y: years

Table 4.5

Mean, Standard Deviation, Median, Inter Quartile Range, |z|, p and r Values of Ratio of Duration of Long and Short Vowels between Age Groups in TDC

Ratio of vowels	4.0-5.11 years				6.0-7.11years						
	Mean	SD	Median	IQR	Mean	SD	Median	IQR	|z|	*p*	*r*
/a/vs /a:/	2.61	0.39	2.36	0.44	2.14	0.44	2.22	0.53	1.73	0.08	0.24
/i/ vs /i:/	1.50	0.47	1.87	0.84	1.88	0.50	1.65	0.87	0.34	0.73	0.05
/u/ vs/u:/	2.29	0.38	2.22	0.66	2.29	0.53	2.21	0.92	0.15	0.88	0.02
/e/ vs /e:/	2.11	0.38	2.20	0.67	2.09	0.40	2.14	0.40	0.00	1.00	0.00
/o/ vs /o:/	2.91	0.36	2.37	0.47	2.31	0.35	2.34	0.50	0.04	0.97	0.01

Note. SD: standard deviation, IQR: interquartile range, *r*: effect size

**p*<0.05, ***p*<0.01

The ratio of duration of long and short vowels was observed to decrease with implant use in children using CI, though the difference was not-significant (*p*>0.05). Similar trend was observed in TDC as well. The ratio was least for high front vowel /i/ and highest for mid back vowel /o/ in both groups irrespective of age. The results of Mann-Whitney U test for comparing ratio of duration of long and short vowels across the groups are provided in Table 4.6.

Table 4.6

Results of Mann Whitney U Test for Comparison of Ratio of Vowel Duration between Children using CI and TDC in both Age Groups

Ratio of vowels	CI vs TDC (4.0-5.11 years)			CI vs TDC (6.0-7.11 years)		
	|z|	*p*	*r*	|z|	*p*	*r*
/a/vs /a:/	2.33	0.02*	0.37	2.50	0.01*	0.40
/i/ vs /i:/	0.40	0.68	0.06	2.07	0.06	0.33
/u/ vs/u:/	0.54	0.58	0.09	0.29	0.77	0.05
/e/ vs /e:/	0.96	0.33	0.15	0.37	0.70	0.06
/o/ vs /o:/	1.57	0.11	0.25	2.16	0.07	0.34

Note. r: effect size

*p<0.05

Ratios of duration of all vowels were found to be higher in children using CI compared to TDC irrespective of age. Results of Mann Whitney U test indicated a significantly higher ratio for /a/ vs /a:/ for both younger (|z|= 2.33, *p*<0.05, *r*=0.37) and older (|z|= 2.50, *p*<0.01,*r*=0.40) groups of children using CI compared to TDC. Interestingly, the upper limit of this ratio in CI was 2.97 which indicate that the long vowel was almost thrice as long as the short vowel.

4.1.1.2. Stops.

The parameters studied for stop consonants included voice onset time (VOT), burst duration (BD) and closure duration (CD).

4.1.1.2.1. Voice Onset Time (VOT).

Voice onset time (VOT) was measured in the word initial position for bilabials (/p/, /b/), dentals (/t/, /d/), retroflex (/ʈ/, /ɖ/) and velars (/k/, /g/).VOT for voiced dental stop /d/ could not be subjected to statistical analysis in the younger age (4.0-5.11 years) in both clinical and control groups because of two reasons. The first one being the age of acquisition of the phoneme was 5.3 years and 10 out of the 15 participants in CI group were below the age of 5 years. Secondly, only correct productions were considered for acoustic analysis and the percentage of misarticulations for dental stop /d/ was high in CI as well as in TDC group. This resulted in insufficient number of data points for statistical analysis of /d/. The mean, standard deviation, median and inter quartile range, |z|, *p* and *r* values of voice onset time between age in CI and TDC are provided in Table 4.7 and 4.8 respectively.

Table 4.7

Mean, Standard Deviation, Median, Inter Quartile Range, |z|, p and r Values of Voice Onset Time (VOT) between 2-3 and 3-4 years of CI Experience

Voice onset time	4.0-5.11y (2-3y of CI use)				6.0- 7.11y (3-4y of CI use)						
	Mean	SD	Median	IQR	Mean	SD	Median	IQR	|z|	*p*	*r*
/p/	10.57	4.83	19.23	7.76	8.07	2.53	7.56	4.45	0.69	0.48	0.13
/b/	52.04	13.99	49.87	13.84	47.82	11.54	45.14	20.73	1.27	0.20	0.23
/t/	9.55	4.54	8.91	3.76	12.24	6.82	10.01	14.11	0.34	0.73	0.06
/d/	-	-	-	-	76.55	9.23	78.53	15.85	-	-	-
/ʈ/	8.02	2.71	8.12	4.16	7.79	3.51	7.08	4.08	0.36	0.71	0.07
/ɖ/	62.48	22.18	59.87	32.16	72.72	14.32	76.43	28.93	0.90	0.36	0.16
/k/	20.54	7.30	23.98	11.75	22.66	12.14	19.44	18.43	0.30	0.76	0.05
/g/	54.57	13.54	50.87	28.43	52.08	25.92	53.48	32.09	0.28	0.77	0.05

Note. SD: Standard deviation, IQR: Interquartile range, *r*: effect size, y: years

Table 4.8

Mean, Standard Deviation, Median, Inter Quartile Range, $\lvert z\rvert$, p and r Values of Voice Onset Time (VOT) between Age Groups in TDC

Voice onset time	4.0-5.11 years				6.0- 7.11 years				$\lvert z\rvert$	*p*	*r*
	Mean	SD	Median	IQR	Mean	SD	Median	IQR			
/p/	8.45	5.20	8.71	3.86	7.84	3.24	7.12	2.89	0.86	0.38	0.12
/b/	53.52	19.93	47.36	26.47	65.54	19.04	47.36	34.48	0.80	0.42	0.11
/t/	13.98	4.39	14.22	5.96	11.90	3.79	12.42	6.15	1.57	0.11	0.22
/d/	-	-	-	-	48.84	13.94	45.36	24.27	-	-	-
/ʈ/	9.31	4.76	8.33	8.14	7.22	4.82	4.66	8.28	1.84	0.06	0.26
/ɖ/	44.45	15.69	45.21	13.27	41.85	15.95	40.74	20.07	0.77	0.44	0.11
/k/	24.26	7.50	22.89	11.59	22.00	8.18	19.94	9.77	1.05	0.29	0.15
/g/	63.12	21.17	63.26	33.17	68.54	20.35	66.17	24.27	0.49	0.62	0.07

Note. SD: standard deviation, IQR: interquartile range, *r*: effect size

In CI, changes in VOT with increasing implant experience was compared statistically and significant differences ($p>0.05$) were not observed in any of the phonemes studied. However a general trend of decrease in VOT was observed with advance in duration of implant use for most phonemes except for dental /t/, retroflex /ɖ/ and velar /k/. Though non-significant ($p>0.05$), age wise decrease in VOT was noted for most of the phonemes in TDC also.

The pattern of change in VOT across places of articulation was documented for unvoiced (lag VOT) and voiced stops (lead VOT) in both groups. The unvoiced and voiced stops in TDC manifested a common trend in VOT with respect to place of articulation i.e. velar > dental > bilabial > retroflex. The only exception to this trend was the voiced stops (lead VOT) in younger group of TDC where the order was velar > bilabial > retroflex. This variation in trend could not be commented upon as voiced dental was not considered for analysis in the younger group as it was a late acquired sound in Malayalam. In children using CI, a similar pattern across places of articulation as that of TDC could not be observed in both unvoiced and voiced stops. However among the unvoiced stops (lag VOT), VOT was the longest for velar /k/ and the shortest for retroflex /ʈ/ in both age groups of children using CI. Further, as expected voiced stops had longer lead VOT than unvoiced stops in both groups. The results of Mann Whitney U test comparing VOT between the groups are provided in Table 4.9.

Table 4.9

Results of Mann Whitney U Test for Comparison of Voice Onset Time (VOT) between Children Using CI and TDC in both Age Groups

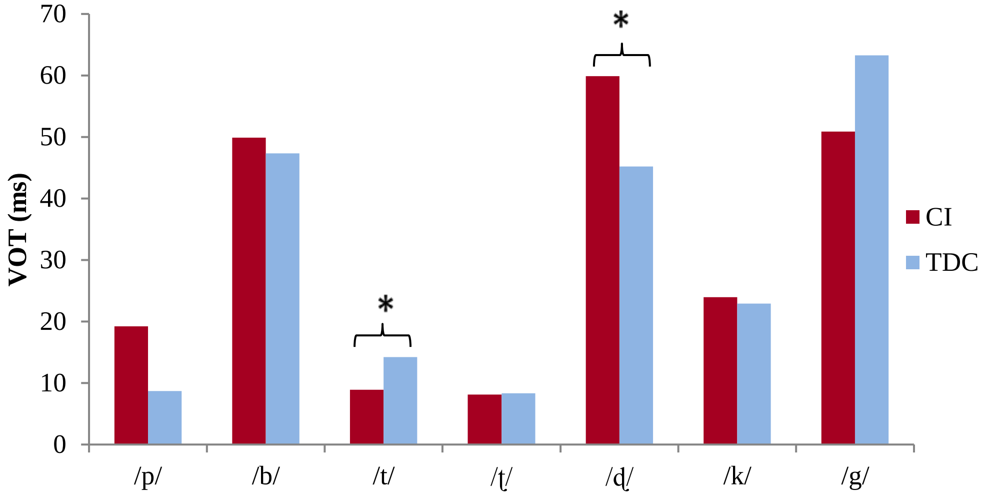
Voice onset time	CI vs TDC (4.0-5.11 years)			CI vs TDC (6.0-7.11 years)		
	|z|	*P*	*r*	|z|	*p*	*r*
/p/	1.07	0.28	0.17	0.23	0.81	0.04
/b/	0.56	0.05	0.09	0.58	0.06	0.09
/t/	2.92	0.00**	0.46	0.08	0.93	0.01
/d/	-	-	-	3.89	0.00**	0.62
/ʈ/	0.51	0.60	0.08	1.46	0.14	0.23
/ɖ/	2.12	0.03*	0.34	4.09	0.00**	0.65
/k/	1.18	0.23	0.19	0.20	0.83	0.03
/g/	0.66	0.50	0.10	0.23	0.81	0.04

Note. $*p<0.05$, $**p<0.01$

Results of Mann Whitney U test indicated a significantly longer lead VOT for voiced retroflex /ɖ/ ($|z|=2.12$, $p<0.05$, $r=0.34$) in younger group of CI compared to TDC. Also, VOT was significantly shorter for unvoiced dental /t/ ($|z|=2.92$, $p<0.01$, $r= 0.46$) in this group. In older age group of CI, VOT (lead VOT) was significantly longer for voiced retroflex /ɖ/ ($|z|=4.09$, $p<0.01$, $r=0.65$) and voiced dental /d/ ($|z|=3.89$, $p<0.01$, $r=0.62$).VOT of bilabials (/p/, /b/), unvoiced retroflex /ʈ/ and velars (/k/, /g/) in CI were comparable to that of TDC irrespective of age. Figure 4.6 and 4.7 represents the VOT in younger and older age groups in children using CI and TDC.

Figure 4.6

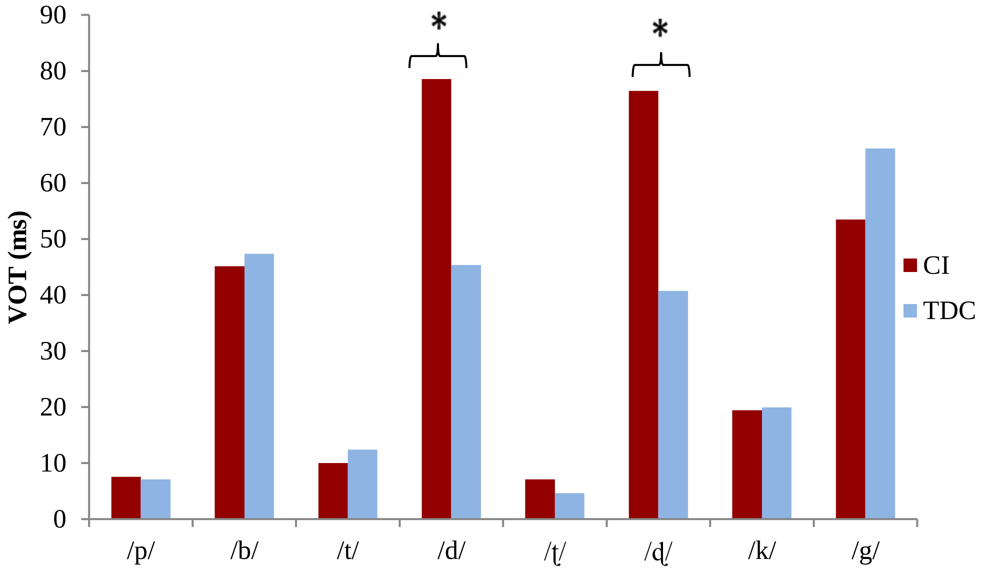
VOT of Stops in Children using CI and TDC in the Age Range of 4.0- 5.11 years



Note. ******p*<0.05

Figure 4.7

VOT of Stops in Children using CI and TDC in the Age Range of 6.0-7.11 years



Note. ******p*<0.05

4.1.1.2.2. Burst Duration.

Burst duration was measured in word initial position for bilabial (/p/, /b/), dental (/t/, /d/), retroflex (/ʈ/, /ɖ/) and velar (/k/, /g/) stops. The voiced dental stop /d/ was not analyzed in younger age group of children due to insufficient number of data points as mentioned for VOT. Mean, standard deviation, median and inter quartile range, |z|, *p* and *r* values of burst duration between age groups in CI and TDC are provided in Table 4.10 and 4.11 respectively.

Table 4.10

Mean, Standard Deviation, Median, Inter Quartile Range, |z|, p and r Values of Burst Duration (BD) between Children with 2-3 and 3-4 years of CI Experience

Burst duration	4.0-5.11y (2-3y of CI use)				6.0- 7.11y (3-4y of CI use)						
	Mean	SD	Median	IQR	Mean	SD	Median	IQR	|z|	*p*	*r*
/p/	2.32	1.31	1.56	1.76	2.47	1.28	2.31	1.76	0.31	0.72	0.06
/b/	1.52	0.63	1.30	0.89	1.23	0.63	1.06	1.01	1.27	0.20	0.23
/t/	3.24	1.48	3.76	2.56	3.34	1.86	2.95	2.32	0.07	0.94	0.01
/d/	-	-	-	-	3.01	1.87	2.76	1.18	-	-	-
/ʈ/	3.70	1.70	3.41	3.09	3.13	1.55	2.38	2.15	0.57	0.56	0.10
/ɖ/	2.79	0.85	3.08	1.05	4.34	1.42	4.53	2.57	2.54	0.01*	0.46
/k/	7.67	4.47	7.53	7.43	6.57	4.40	5.37	4.70	0.52	0.59	0.09
/g/	5.79	2.66	6.66	5.07	5.72	1.91	5.12	2.58	0.28	0.77	0.05

Note. SD: standard deviation, IQR: interquartile range; *r*: effect size, y: years

*****p<0.05

A non-significant reduction in burst duration was noted with increase in implant experience for all stops except unvoiced bilabial /p/ and voiced retroflex /ɖ/. Among the two phonemes (/p/ &/ɖ/), only /ɖ/ (|z|=2.54, *p*<0.05, *r* = 0.46) manifested a significant increase in BD with increasing implant use.

Table 4.11

Mean, Standard Deviation, Median, Inter Quartile Range, |z|, p and r Values of Burst Duration (BD) between Age Groups in TDC

Burst duration	4.0-5.11 years				6.0-7.11 years						
	Mean	SD	Median	IQR	Mean	SD	Median	IQR	|z|	*p*	*r*
/p/	1.79	0.96	1.63	1.22	1.69	0.92	1.44	1.13	0.30	0.76	0.04
/b/	1.66	0.38	1.59	0.64	1.38	0.63	1.25	0.50	2.49	0.01*	0.35
/t/	5.28	2.44	4.61	3.45	4.88	2.36	4.52	4.23	1.40	0.16	0.20
/d/	-	-	-	-	4.18	1.94	4.36	4.00	-	-	-
/ʈ/	3.82	1.88	3.54	2.03	2.54	1.42	2.51	2.47	2.41	0.01*	0.34
/ɖ/	3.21	1.34	2.72	1.21	2.38	1.19	2.26	1.72	2.15	0.03*	0.30
/k/	10.18	4.15	10.07	3.29	8.34	3.60	7.49	3.99	2.00	0.04*	0.28
/g/	6.72	3.21	6.96	5.19	5.24	2.40	5.32	2.72	1.82	0.06	0.26

Note. SD: standard deviation, IQR: interquartile range, *r*: effect size

*$p<0.05$

In TDC, BD decreased with age for all the phonemes and a significant reduction ($p<0.05$) was noted for bilabial /b/ (|z|=2.49, $p<0.05$, $r=0.39$), retroflex /ʈ/ (|z|=2.41, $p<0.05$, $r=0.38$), /ɖ/ (|z|=2.15, $p<0.05$, $r=0.34$) and velar /k/ (|z|=2.00, $p<0.05$, $r=0.32$). Among unvoiced stops, BD was the longest for velar (/k/) followed by dental (/t/), retroflex (/ʈ/) and the shortest for bilabial (/p/) in children using CI as well as TDC irrespective of age. Among voiced stops, the younger age groups of children using CI and TDC followed a similar order i.e. velar > retroflex > bilabial. However the older age group of participants did not demonstrate such a common trend between the groups.

In older group of TDC, the decreasing order of BD voiced stops was similar to that of unvoiced stops, as follows: velar > dental > retroflex > bilabial. The trend exhibited by older group of children using CI was as follows: velars > retroflex >

dental > bilabial. To conclude, BD was the longest for velars and the shortest for bilabials for both unvoiced and voiced stops in both groups. Additionally, unvoiced stops exhibited longer BD compared to voiced stops in both groups except for retroflex stops in older group of children using CI. The results of Mann Whitney U test for comparing BD between the groups are provided in Table 4.12.

Table 4.12

Results of Mann Whitney U Test for Comparison of Burst Duration (BD) between Children using CI and TDC in both Age Groups

Burst duration (BD)	CI vs TDC (4.0-5.11 years)			CI vs TDC (6.0-7.11 years)		
	|z|	*P*	*r*	|z|	*p*	*r*
/p/	1.06	0.28	0.17	2.01	0.05	0.32
/b/	0.90	0.36	0.14	0.98	0.32	0.15
/t/	2.33	0.01*	0.37	1.12	0.26	0.18
/d/	-	-	-	2.17	0.03*	0.34
/ʈ/	0.06	0.95	0.01	1.45	0.14	0.23
/ɖ/	0.18	0.85	0.03	3.35	0.00**	0.53
/k/	3.64	0.00**	0.58	2.60	0.01*	0.41
/g/	0.56	0.57	0.09	0.75	0.45	0.12

Note. r: effect size

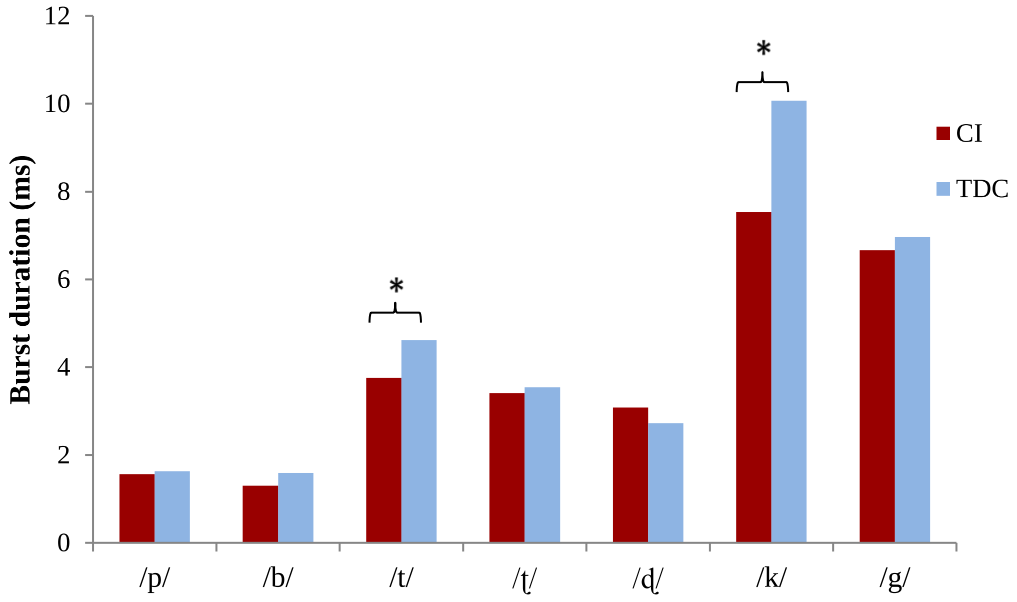
**p*<0.05, ***p*<0.01

In younger age group, BD was significantly shorter for dental /t/ (|z|= 2.33, *p*<0.05, *r*= 0.37) and velar /k/ (|z|=3.64, *p*<0.01, *r*=0.58) in children using CI compared to TDC as observed in Table 4.12. Effect size of velar /k/ was greater than dental /t/. BD of all the other phonemes (/p/,/b/,/ʈ/,/ɖ/,/g/) in children using CI approached normal values (*p*>0.05). However, an overall trend indicated that BD was shorter for most of the phonemes in CI compared to TDC.

In the older age group, BD was shorter for bilabial /p/ and retroflex /ɖ/ in CI compared to TDC. Among these phonemes, retroflex stop /ɖ/ ($|z|=3.35$, $p<0.01$, $r=0.53$) demonstrated a significantly longer BD in children using CI. BD was significantly shorter for dental /d/ ($|z|=2.17$, $p<0.05$, $r=0.34$) and velar /k/ ($|z|=2.60$, $p<0.05$, $r=0.41$) in CI compared to TDC. Higher effect size (*r)* was noted for /ɖ/ followed by /k/ and /d/. To conclude, most of the phonemes in children using CI manifested near normal measures for BD. Figure 4.8 and 4.9 depict the BD in younger and older age groups in children using CI and TDC.

Figure 4.8

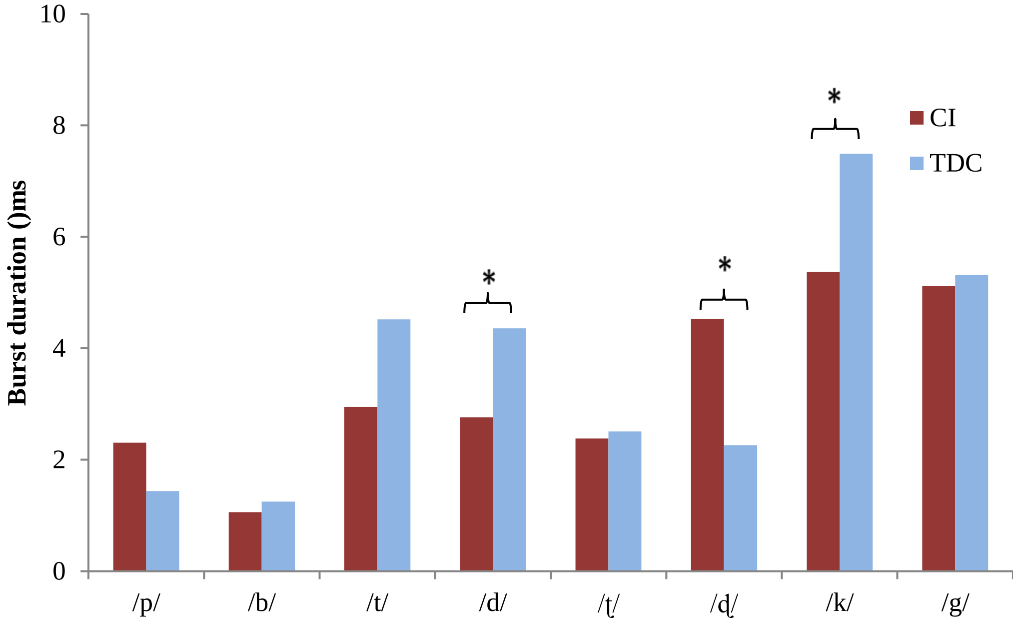
Burst Duration of Stops in Children using CI and TDC in the Age Range of 4.0-5.11 years



Note. *$p<0.05$

Figure 4.9

Burst Duration of Stops in Children using CI and TDC in the Age Range of 6.0-7.11 years



Note. *p<*0.05*

4.1.1.2.3. Closure Duration.

Closure duration was measured in word medial position for bilabial (/p/, /b/), alveolar (/r/), dental (/t/, /d/), retroflex (/ʈ/, /ɖ/) and velar (/k/, /g/) stops. As stated earlier for VOT and BD, voiced dental /d/ was not considered for analysis in the younger age group. Mean, standard deviation, median and inter quartile range, |z|, *p* and *r* values of closure duration in CI and TDC groups are tabulated in Table 4.13 and Table 4.14.

Table 4.13

Mean, Standard Deviation, Median, Inter Quartile Range, |z|, p and r Values of Closure Duration (CD) between 2-3 and 3-4 years of CI Experience

Closure duration	4.0-5.11y (2-3y of CI use)				6.0- 7.11y (3-4y of CI use)						
	Mean	SD	Median	IQR	Mean	SD	Median	IQR	|z|	*p*	*r*
/p/	186.06	39.53	187.56	76.31	191.41	41.45	188.65	52.66	0.41	0.67	0.07
/b/	182.24	34.72	184.97	60.37	181.54	46.45	159.88	50.96	0.34	0.73	0.06
/r̠/	151.83	22.77	147.26	35.16	134.13	17.13	132.53	21.53	1.67	0.09	0.30
/t/	286.61	70.58	247.08	91.28	281.98	45.99	282.08	80.35	0.33	0.73	0.06
/d/	-	-	-	-	108.16	17.18	116.51	26.95	-	-	-
/ʈ/	373.77	87.27	367.17	109.93	309.50	64.34	330.71	109.62	2.16	0.03*	0.39
/ɖ/	95.51	21.39	99.01	24.12	102.26	14.41	101.65	9.88	0.89	0.37	0.16
/k/	177.82	42.34	163.45	76.91	178.93	45.22	167.18	61.99	0.23	0.81	0.04

Note. SD: standard deviation, IQR: interquartile range; *r*: effect size, y: years

*$p<0.05$

Table 4.14

Mean, Standard Deviation, Median, Inter Quartile Range, |z|, p and r Values of Closure Duration (CD) between Age Groups in TDC

Closure duration	4.0-5.11 years				6.0-7.11 years						
	Mean	SD	Median	IQR	Mean	SD	Median	IQR	|z|	*p*	*r*
/p/	166.38	35.49	161.78	49.98	144.23	28.53	142.73	31.31	1.92	0.06	0.27
/b/	118.34	35.52	110.12	49.91	116.16	29.25	115.35	49.14	0.09	0.92	0.01
/r̠/	108.98	21.68	115.31	41.72	104.16	14.63	104.36	25.78	0.91	0.36	0.13
/t/	234.17	32.47	233.51	37.62	224.94	47.76	215.21	43.12	1.36	0.17	0.19
/d/	-	-	-	-	84.23	15.32	87.61	23.81	-	-	-
/ʈ/	254.94	37.75	241.46	44.75	226.26	56.28	224.71	84.91	1.85	0.06	0.26
/ɖ/	92.23	28.78	97.13	39.08	87.45	16.63	93.66	20.03	0.81	0.42	0.11
/k/	136.71	20.44	135.66	27.02	130.02	24.39	132.21	37.11	1.04	0.29	0.15

Note. SD: standard deviation, IQR: interquartile range, *r*: effect size

Closure duration did not demonstrate any consistent pattern of change with increase in implant experience in the CI group. However, a significant decrease in CD with advance in implant use was noted for retroflex /ʈ/ ($|z|=2.16$, $p<0.05$, $r=0.34$) and velar /g/ ($|z|=2.51$, $p<0.05$, $r= 0.40$). In TDC, CD decreased with age for all the phonemes except /b/. However none of the phonemes tested exhibited significant difference ($p>0.05$) with increase in age.

Comparisons were made with respect to place of articulation and voicing feature. Among unvoiced stops, both CI and TDC groups exhibited a uniform pattern in CD irrespective of age and the pattern is as follows: retroflex > dental > bilabial > velar > alveolar which is unlike VOT and BD. For voiced stops in TDC, the deceasing order of closure duration in older group was as follows: bilabial > retroflex >velar > dental. The pattern was almost similar in the younger group of TDC i.e. bilabial > retroflex > velar. However it was difficult to compare the pattern between age groups as dental stop (/d/) was not studied in the younger group. For voiced stops in children using CI, apart from bilabial having the longest CD, no trend in CD across places of articulation could be observed. Further, closure duration was observed to be longer for unvoiced stops in both groups of participants. Mann-Whitney U test was employed to analyze statistical significance in CD across groups and the results are tabulated in Table 4.15.

Table 4.15

Results of Mann Whitney U Test for Comparison of Closure Duration in Children using CI and TDC in both Age Groups

Closure duration	CI vs TDC (4.0-5.11 years)			CI vs TDC (6.0-7.11 years)		
	|z|	*p*	*r*	|z|	*p*	*r*
/p/	1.49	0.13	0.24	2.47	0.01*	0.39
/b/	3.69	0.00**	0.58	3.98	0.00**	0.63
/t/	2.27	0.02*	0.36	3.13	0.00**	0.49
/d/	-	-	-	3.27	0.00**	0.52
/r̠/	4.13	0.00**	0.65	3.86	0.00**	0.61
/ʈ/	4.51	0.00**	0.71	3.47	0.00**	0.55
/ɖ/	0.48	0.62	0.08	2.41	0.02*	0.38
/k/	2.86	0.00**	0.45	2.27	0.02*	0.36
/g/	3.00	0.00**	0.47	0.32	0.74	0.05

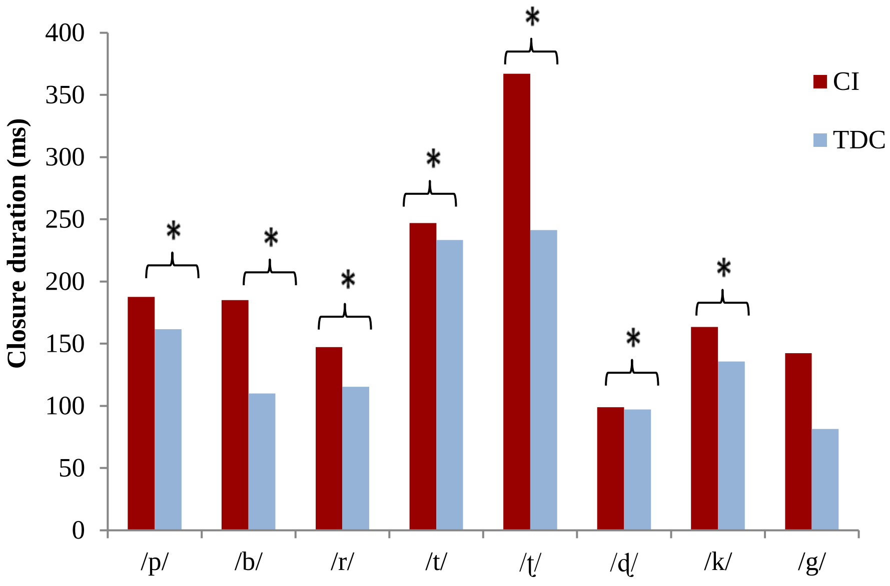
Note. r: effect size

**p*<0.05, ***p*<0.01

Across group comparisons revealed that CI group had longer CD compared to TDC. In the younger group, CD was significantly longer (*p*<0.05) for all the phonemes except /p/ and /ɖ/ in CI compared to TDC. In the older age group, CD was significantly longer (*p*<0.05) for all phonemes except voiced velar stop /g/. To conclude, CD in children using CI was significantly deviant from that of TDC for majority of the phonemes studied. Also no significant improvement was noted in CD with increase in implant age. Among the temporal parameters of stops investigated in the present study, CD can be considered as the most affected in children using CI. Figure 4.10 and 4.11 depict the CD in younger and older age groups in children using CI and TDC.

Figure 4.10

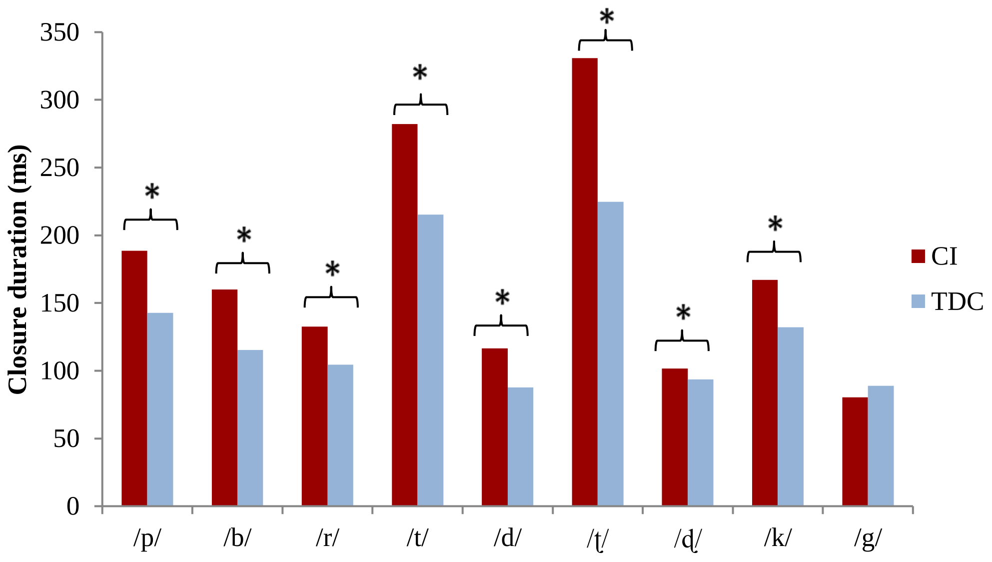
Closure Duration of Stops in Children using CI and TDC in the Age Range of 4.0-5.11 years



**p*<0.05

Figure 4.11

Closure Duration of Stops in Children using CI and TDC in the Age Range of 6.0-7.11 years



**p*<0.05

4.1.1.3. Nasals.

The temporal parameter investigated for nasals in the present study was nasal consonant duration (NCD). It was measured for bilabial /m/, dental /n̪/, alveolar /n/, retroflex /ɳ/ palatal /ɲ/, and velar /ŋ/ in the word medial position. Mean, standard deviation, median, and inter quartile range, |z|, *p* and *r* values of NCD in CI and TDC groups are provided in Table 4.16 and 4.17 respectively.

Table 4.16

Mean, Standard Deviation, Median, Inter Quartile Range, |z|, *p and r Values of Nasal Consonant Duration (NCD) between Children with 2-3 and 3-4 years of CI Experience*

NCD	4.0-5.11y (2-3y of CI use)				6.0- 7.11y (3-4y of CI use)						
	Mean	SD	Median	IQR	Mean	SD	Median	IQR	|z|	*p*	*r*
/m/	318.32	61.61	354.74	77.76	328.03	69.39	341.46	90.26	0.51	0.60	0.09
/n̪/	315.35	91.57	322.66	142.01	304.45	84.73	309.59	115.56	0.30	0.76	0.05
/n/	117.09	29.96	118.51	38.30	86.93	26.14	82.18	38.87	2.33	0.02*	0.43
/ɳ/	134.20	47.43	128.50	14.70	100.65	29.35	98.54	24.64	2.74	0.00**	0.50
/ɲ/	310.32	69.09	296.83	119.19	299.83	101.3	280.66	53.70	0.74	0.45	0.14
/ŋ/	122.02	36.28	129.36	44.24	102.11	21.74	105.02	19.61	1.50	0.13	0.27

Note. SD: standard deviation, IQR: interquartile range; *r*: effect size, y: years

**p*<0.05, ***p*<0.01,

Table 4.17

Mean, Standard Deviation, Median, Inter Quartile Range, |z|, *p and r Values of Nasal Consonant Duration (NCD) between Age Groups in TDC Group*

NCD	4.0-5.11 years				6.0- 7.11 years						
	Mean	SD	Median	IQR	Mean	SD	Median	IQR	|z|	*p*	*r*
/m/	249.35	50.46	232.91	46.79	236.94	47.69	230.09	75.19	0.86	0.38	0.12
/n̪/	236.59	47.77	230.90	60.13	218.00	29.62	219.22	49.81	1.88	0.05	0.27
/n/	82.74	14.54	81.90	23.08	79.63	15.81	80.95	26.71	0.60	0.54	0.08
/ɳ/	63.94	20.34	59.42	44.24	61.38	18.43	58.01	36.78	0.58	0.55	0.08
/ɲ/	224.36	41.45	228.76	62.71	217.19	49.49	217.79	50.91	0.35	0.72	0.05
/ŋ/	108.42	16.32	114.62	26.60	103.33	19.32	99.46	32.44	0.58	0.56	0.08

Note. SD: standard deviation, IQR: interquartile range, *r*: effect size

Comparison of sub groups of CI indicated a significant reduction in nasal consonant duration with increase in implant experience for alveolar /n/ (|z|=2.33, *p*<0.05, *r*=0.43) and retroflex /ɳ/ (|z|= 2.74, *p*<0.01, *r*=0.50) in children using CI. The median values indicated a decrease in nasal consonant duration reduced for all nasal phonemes with increase in duration of CI use, though the difference was non-significant (*p*>0.05). Similarly a non-significant (*p*>0.05) age dependent decrease in the duration of all nasal phonemes was noted in TDC.

NCD exhibited a unique pattern with respect to place of articulation in each group irrespective of age. In TDC, the decreasing order of NCD was as follows: bilabial > dental > palatal > velar > alveolar > retroflex. However in children using CI, a slightly different pattern was noticed i.e. bilabial > dental > palatal > velar > retroflex> alveolar. Overall, bilabial nasal /m/ demonstrated the longest duration in both groups. Mann Whitney U test was employed to analyze statistical significance in NCD between groups and the results are tabulated in Table 4.18.

Table 4.18

Results of Mann Whitney U Test for Comparison of Nasal Consonant Duration in Children using CI and TDC in both Age Groups

NCD	CI vs TDC (4.0-5.11 years)			CI vs TDC (6.0-7.11 years)		
	|z|	*P*	*r*	|z|	*p*	*r*
/m/	3.31	0.00**	0.52	3.56	0.00**	0.56
/n̪/	2.45	0.01*	0.39	3.58	0.00**	0.57
/n/	3.57	0.00**	0.56	0.79	0.42	0.12
/ɳ/	4.42	0.00**	0.70	3.80	0.00**	0.60
/ɲ/	3.74	0.00**	0.59	3.22	0.00**	0.51
/ŋ/	1.25	0.21	0.20	1.23	0.22	0.19

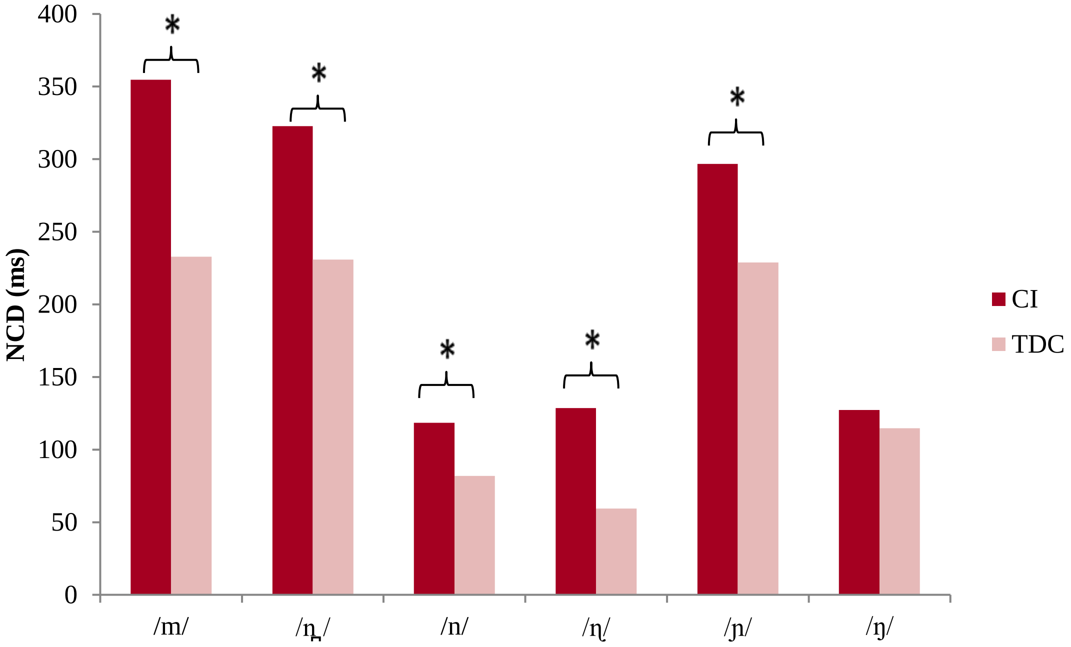
Note. *r*: effect size

**p*<0.05, ***p*<0.01

Results of Mann-Whitney U test indicated a significantly longer duration ($p<0.05$) for all nasal phonemes except for velar /ŋ/ ($p>0.05$) in the younger group of children using CI. Higher r value was noted for retroflex /ɳ/ followed by palatal /ɲ/ and alveolar/n/ in younger group. Except alveolar /n/ and velar /ŋ/ ($p>0.05$), the older age group of CI, of CI demonstrated a significantly longer ($p<0.05$) NCD with higher effect size (r value) noted for retroflex /ɳ/ followed by bilabial /m/ and dental /n̪/. To conclude, Compared to TDC, NCD was significantly longer in children using CI for most of the phonemes (/m/, /n̪/, /ɳ/, & /ɲ/) even after 3-4 years of CI use. Figure 4.12 and 4.13 depict NCD in younger and older age groups in children using CI and TDC.

Figure 4.12

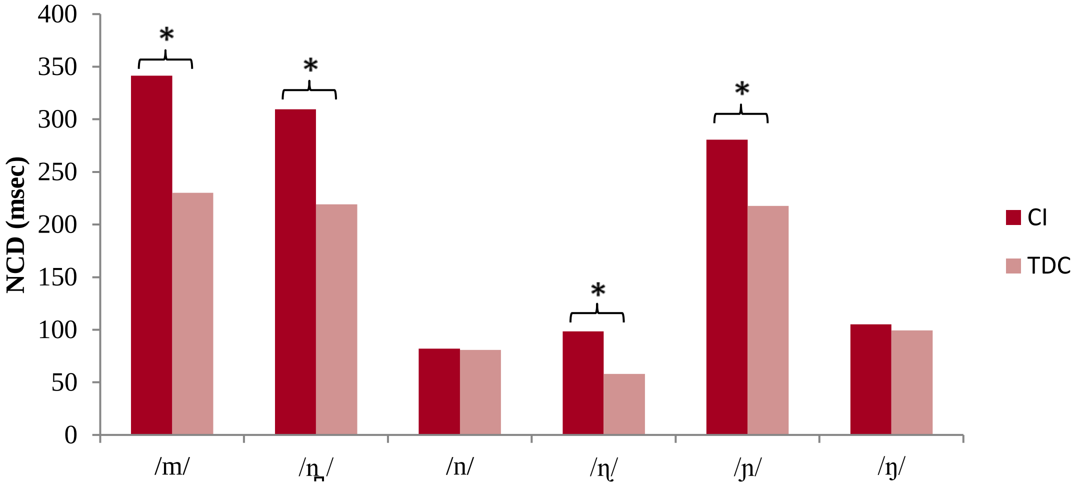
Nasal Consonant Duration in Children using CI and TDC in the Age Range of 4.0-5.11 years



Note. *$p<0.05$

Figure 4.13

Nasal Consonant Duration in Children using CI and TDC in the Age Range Of 6.0-7.11 years



Note. *p<0.05

4.1.1.4. Fricatives.

The temporal parameter investigated for fricatives in the present study was frication duration (FD). FD was measured for alveolar (/s/), palatal (/ʃ/) and retroflex (/ʂ/) fricatives in the word initial position. The mean, standard deviation, median, and inter quartile range, |z|, *p* and *r* values of frication duration in CI and TDC groups are provided in Table 4.19 and 4.20 respectively.

Table 4.19

Mean, Standard Deviation, Median, Inter Quartile Range, |z|, p and r Values of Frication Duration (FD) between Children with 2-3 and 3-4 years of CI Experience

Frication duration	4.0-5.11y (2-3y of CI use)				6.0- 7.11y (3-4y of CI use)						
	Mean	SD	Median	IQR	Mean	SD	Median	IQR	|z|	*p*	*r*
/s/	195.5	56.86	212.84	111.22	139.39	28.88	138.41	50.2	2.28	0.02*	0.42
/ʃ/	164.73	43.56	159.36	32.89	156.10	43.62	165.96	87.71	0.18	0.85	0.03
/ʂ/	226.58	108.08	182.19	215.11	147.36	44.12	143.93	97.49	1.79	0.07	0.33

*Note.*SD: standard deviation, IQR: interquartile range; *r*: effect size, y: years
*p<0.05,

Table 4.20

Mean, Standard Deviation, Median, Inter Quartile Range, |z|, p and r Values of Frication Duration between Age Groups in TDC Group

Frication duration	4.0-5.11 years				6.0- 7.11 years						
	Mean	SD	Median	IQR	Mean	SD	Median	IQR	|z|	*p*	*r*
/s/	133.77	30.14	136.32	24.98	131.12	30.39	133.51	43.58	0.61	0.53	0.09
/ʃ/	161.91	32.18	155.12	42.95	155.56	41.90	153.34	41.87	0.49	0.62	0.07
/ʂ/	120.49	26.73	116.27	38.69	129.30	23.38	129.69	40.42	1.20	0.23	0.17

Note. SD: standard deviation, IQR: interquartile range, *r*: effect size

**p*<0.05

As evidenced from Table 4.19, there was a reduction in FD with increase in implant experience in children using CI for all fricatives except dental /s/. A significant decrease in FD towards normal limit was noted with increase in CI use for alveolar fricative /s/ (|z|=2.28, *p*<0.02, *r*=0.42). In TDC, FD decreased with age, however a significant reduction with age was not present for any of the fricatives in this group as observed in Table 4.20. With respect to place of articulation, palatal fricative /ʃ/ was observed to have the longest FD followed by alveolar /s/ and retroflex /ʂ/ in both age groups of TDC; however, a uniform pattern was not demonstrated by CI group. Mann Whitney U test was employed to analyze statistical significance in FD between CI and TDC and the results are tabulated in Table 4.21.

Table 4.21

Results of Mann Whitney U Test for Comparison of Frication Duration in Children Using CI and TDC in both Age Groups

Frication duration	CI vs TDC (4.0-5.11 years)			CI vs TDC (6.0-7.11 years)		
	|z|	*p*	*r*	|z|	*p*	*r*
/s/	2.57	0.01*	0.41	0.28	0.77	0.04
/ʃ/	0.22	0.82	0.03	0.08	0.93	0.01
/ʂ/	3.45	0.00**	0.55	0.94	0.34	0.15

Note. r: effect size

**p*<0.05, ***p*<0.01

Findings of Mann Whitney U test for comparison across groups revealed that in younger group, FD of alveolar /s/ (|z|= 2.57, *p*<0.05, *r*=0.41) and retroflex /ʂ/ (|z|= 3.45, *p*<0.01, *r*=0.55) was significantly longer for children using CI. However, FD of palatal /ʃ/ in CI group approached towards normality. Interestingly, though fricatives are late in speech acquisition and difficult to produce, FD of all phonemes approached normal limits with 3-4 years of CI experience. Apart from this, palatal /ʃ/ was observed to be the first phoneme to approach typical values among the fricatives studied.

4.1.1.5. Affricates.

Affrication duration (AD) was measured for unvoiced (/c/) and voiced (/ɟ/) palatal affricates in the word initial position. The mean, standard deviation, median, and inter quartile range, |z|, p and r values of affrication duration in CI and TDC groups were measured and are provided in Table 4.22 and 4.23 respectively.

Table 4.22

Mean, Standard Deviation, Median, Inter Quartile Range, |z|, p and r Values of Affrication Duration (AD) between Children with 2-3 and 3-4 years of CI Experience

Affrication duration	4.0-5.11y (2-3y of CI use)				6.0- 7.11y (3-4y of CI use)						
	Mean	SD	Median	IQR	Mean	SD	Median	IQR	|z|	*p*	*r*
/c/	81.17	30.11	83.28	33.06	72.46	26.09	74.59	46.84	0.64	0.52	0.12
/ɟ/	83.32	18.09	82.41	25.58	71.45	30.14	73.33	63.02	0.85	0.39	0.16

Note. SD: standard deviation, IQR: interquartile range, *r*: effect size, y: years

Table 4.23

Mean, Standard Deviation, Median, Inter Quartile Range, |z|, p and r Values of Affrication Duration (AD) between Age Groups in TDC Group

Affrication Duration	4.0-5.11 years				6.0-7.11 years						
	Mean	SD	Median	IQR	Mean	SD	Median	IQR	|z|	*p*	*r*
/c/	83.94	18.32	82.52	25.79	73.84	18.77	68.72	19.94	2.16	0.03*	0.31
/ɟ/	59.74	22.92	63.26	45.6	57.43	20.43	46.91	39.08	0.29	0.76	0.04

SD: standard deviation, IQR: interquartile range, *r*: effect size

**p*<0.05

Affrication duration reduced and approached normal limits with increase in CI experience. Similarly in TDC, there was an age wise decrease in affrication duration, with a significant decrease noted for unvoiced palatal /c/ (|z|= 2.16, *p*<0.05, *r*=0.34). Unvoiced affricate /c/ exhibited longer duration compared to voiced /ɟ/ in both groups. Mann Whitney U test was employed to analyze statistical significance in AD between the groups and the results are tabulated in Table 4.24.

Table 4.24

Results of Mann Whitney U Test for Comparison of Affrication Duration in Children using CI and TDC in both Age Groups

Affrication Duration	CI vs TDC (4.0-5.11 years)			CI vs TDC (6.0-7.11 years)		
	|z|	*p*	*r*	|z|	*p*	*r*
/c/	0.71	0.47	0.11	0.04	0.96	0.01
/ɟ/	2.62	0.00**	0.41	1.16	0.24	0.18

***p*<0.01

Across group comparisons revealed that AD was longer in children using CI compared to TDC as seen in Table 4.22 and Table 4.23. Affrication duration of voiced /ɟ/ (|z|=2.62, *p*<0.01, *r*=0.41) was significantly longer in the younger CI group, although unvoiced /c/ showed similar values to that of TDC. In the older group of children using CI, AD of both unvoiced and voiced affricates approached normal limits.

4.1.1.6. Word duration.

Word duration (WD) was measured for words with the target vowels (5 short and 5 long) in the word initial position. The mean, standard deviation, median, and inter quartile range, |z|, *p* and *r* values of word duration for short and long vowels in CI and TDC groups were measured and are provided in Table 4.25 and Table 4.26.

Table 4.25

Mean, Standard Deviation, Median, Inter Quartile Range, |z|, *p and r Values of Word Duration between Children with 2-3 and 3-4 years of CI Experience*

Word duration	4.0-5.11y (2-3y of CI use)				6.0- 7.11y (3-4y of CI use)						
	Mean	SD	Median	IQR	Mean	SD	Median	IQR	|z|	*p*	*r*
/a/	799.14	140.99	825.26	217.77	736.18	104.23	737.66	115.24	1.51	0.13	0.28
/i/	708.17	137.44	735.41	227.2	622.65	101.75	606.11	78.68	1.72	0.08	0.31
/u/	774.17	101.88	787.88	186.04	733.61	113.56	727.41	102.22	0.97	0.33	0.18
/e/	734.12	114.44	740.77	157.55	597.54	103.57	617.69	78.45	2.71	0.00*	0.49
/o/	755.37	143	805.62	305.90	641.96	133.41	629.16	142.50	2.05	0.04*	0.37
/a:/	844.21	183.46	875.01	298.92	734.58	132.79	684.21	48.33	1.72	0.08	0.31
/i:/	817.02	204.63	818.04	253.49	769.54	135.90	766.16	140.37	0.60	0.54	0.11
/u:/	893.26	113.21	901.74	204.67	851.17	136.34	850.96	95.36	1.05	0.29	0.19
/e:/	799.94	111.80	806.67	200.51	742.61	159.95	725.39	3.88	1.05	0.29	0.19
/o:/	755.18	134.73	814.38	260.49	773.71	165.92	708.61	108.7	0.10	0.91	0.02

Note. SD: standard deviation, IQR: interquartile range; *r*: effect size, y: years

**p*<0.05,

Table 4.26

Mean, Standard Deviation, Median, Inter Quartile Range, |z|, p and r Values of Word Duration between Age Groups in TDC Group

Word duration	4.0-5.11y (2-3y of CI use)				6.0- 7.11y (3-4y of CI use)						
	Mean	SD	Median	IQR	Mean	SD	Median	IQR	|z|	*p*	*r*
/a/	640.65	111.55	609.06	203.52	627.58	81.36	603.87	115.24	0.04	0.96	0.01
/i/	497.63	84.08	504.81	146.32	467.59	68.54	479.65	78.68	1.36	0.17	0.19
/u/	620.52	84.18	599.51	110.83	583.74	82.33	598.51	102.22	1.45	0.14	0.21
/e/	571.53	92.64	555.02	93.96	521.72	80.39	519.61	78.45	2.18	0.02*	0.31
/o/	621.19	96.67	630.64	94.33	598.20	88.35	610.87	142.50	0.59	0.55	0.08
/a:/	643.87	75.42	629.95	94.13	623.63	70.23	622.75	48.33	0.51	0.60	0.07
/i:/	655.79	120.02	676.56	148.5	657.92	88.90	633.23	140.37	0.01	0.99	0.00
/u:/	700.01	78.32	691.41	79.93	650.45	64.09	658.06	95.36	2.33	0.02*	0.33
/e:/	672.22	87.52	634.28	122.23	644.80	107.45	625.81	73.88	1.04	0.29	0.15
/o:/	641.82	95.68	635.53	67.33	618.41	95.98	628.13	108.7	0.56	0.57	0.08

Note. SD: standard deviation, IQR: interquartile range, *r*: effect size

**p*<0.05

Word duration was found to decrease with increase in implant experience with a significantly longer duration for words with short vowels /e/ (|z|=2.71, *p*< 0.01, *r*=0.49) and /o/ (|z|= 2.05, *p*<0.05, *r*=0.37). In TDC, WD decreased with age with a significant reduction for words with short vowel /e/ (|z|=2.18, p<0.05, *r*=0.34) and long vowel /u:/ (|z|= 2.33, p<0.05, *r*=0.37). In both younger and older CI groups, among the short vowels, words with vowel /a/ demonstrated the longest WD, whereas words with long vowel /u:/ demonstrated longest duration among long vowels. In TDC, the increasing order of WD was with the following vowels in order: /o/>/a/>/u/>/e/>/i/ (short vowels); and /u:/>/i:/>/o:/>/e:/>/a:/ (long vowels) for both age groups. However, such a uniform trend was not observed in CI group. Mann Whitney U test was employed for group comparison and is provided in Table 4.27.

Table 4.27

Results of Mann Whitney U Test for Comparison of Word Duration in Children using CI and TDC in both Age Groups

Word duration	CI vs TDC (4.0-5.11 years)			CI vs TDC (6.0-7.11 years)		
	|z|	*p*	*r*	|z|	*p*	*r*
/a/	3.45	0.00**	0.55	3.28	0.00**	0.52
/i/	4.20	0.00**	0.66	4.29	0.00**	0.68
/u/	3.81	0.00**	0.60	3.50	0.00**	0.55
/e/	3.81	0.00**	0.60	2.44	0.02	0.39
/o/	2.72	0.00**	0.43	1.24	0.21	0.20
/a:/	3.36	0.00**	0.53	2.50	0.01*	0.40
/i:/	2.50	0.01*	0.40	2.72	0.00**	0.43
/u:/	4.40	0.00**	0.70	3.84	0.00**	0.61
/e:/	3.34	0.00**	0.53	1.94	0.05	0.31
/o:/	2.69	0.00**	0.43	2.78	0.00**	0.44

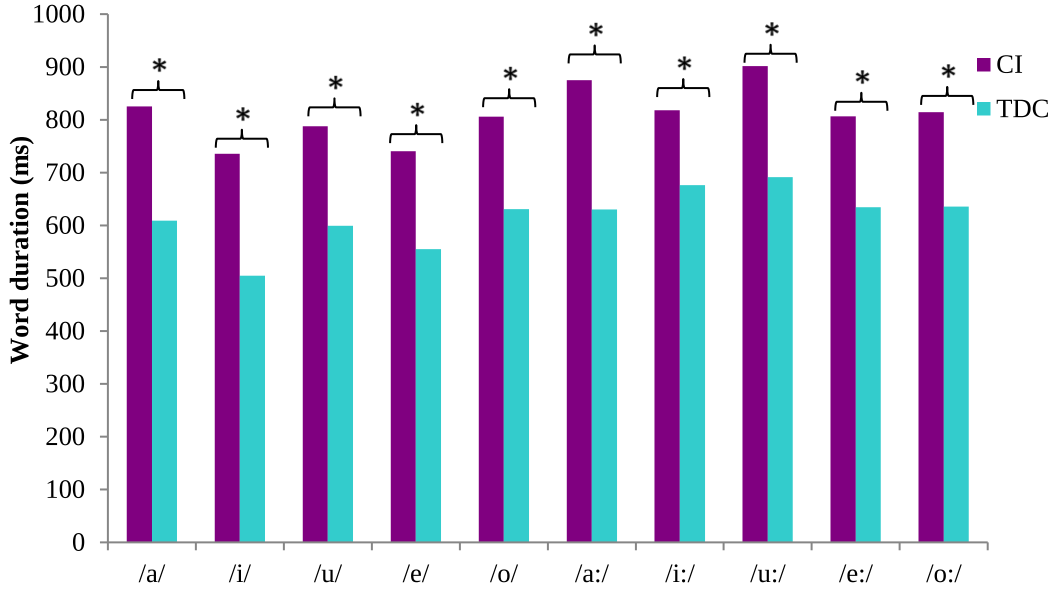
Note. r: effect size

**p*<0.05, ***p*<0.01

As noted in Table 4.27, a significantly longer (p<0.05) duration for all words were observed in younger group of children using CI. In older age group, duration of words with vowels /o/, /e/ and /e:/ reduced considerably and was found to move towards normal limits. However a significantly longer (p<0.05) duration for other words were noted. To conclude, majority of the vowels continued to exhibit compensatory lengthening as observed in other temporal measures investigated in the present study. Figure 4.14 and Figure 4.15 depict word duration in younger and older age groups in children using CI and TDC.

Figure 4.14

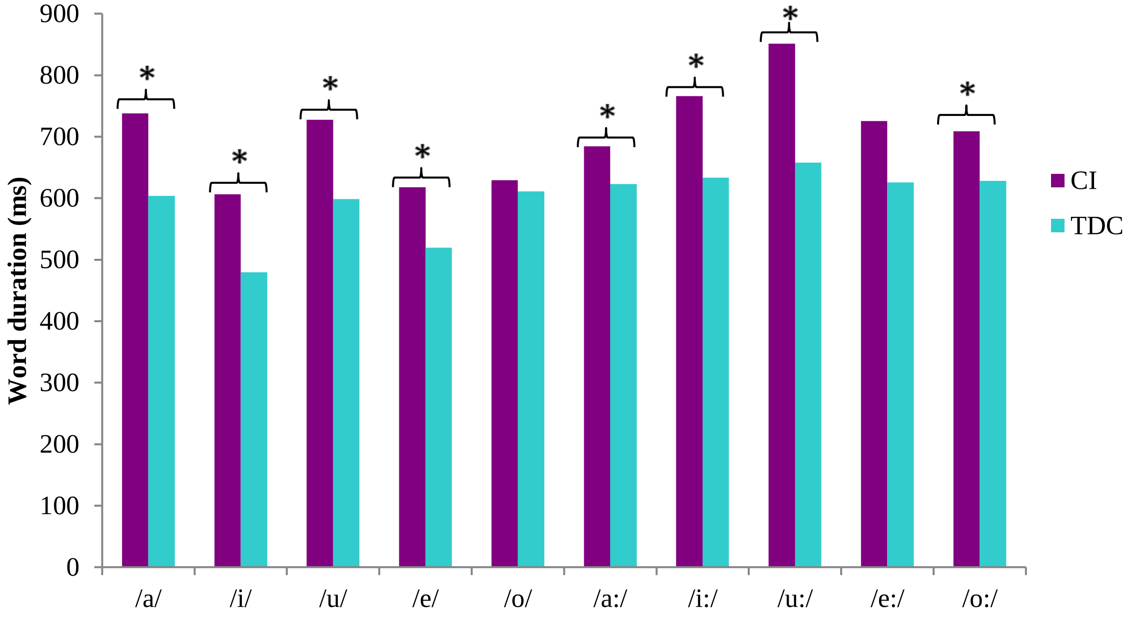
Word Duration in Children using CI and TDC in the Age Range of 4.0-5.11 years



Note. *p<0.05

Figure 4.15

Word Duration in Children using CI and TDC in the Age Range Of 6.0-7.11 years



Note. *p<0.05

4.1.2. Spectral Parameters

Spectral measures of vowels and nasals were investigated in the present study. Hence the results will be discussed under the sound class vowels and nasals.

4.1.2.1. Vowels.

The spectral measures of vowels considered in the present study included fundamental frequency (F_0), first and second formant frequencies (F_1 & F_2) and Vowel space area (VSA).

4.1.2.1.1. Fundamental Frequency.

Fundamental frequency (F_0) was measured from the phonation of vowel /a/. The mean, standard deviation, median, and inter quartile range, |*z*|, *p* and *r* values of F_0 in CI and TDC are provided in Table 4.28.

Table 4.28

Mean, Standard Deviation, Median, Inter Quartile Range, |*z*|, *p and r Values of Fundamental Frequency (F_0) between Age Groups in CI and TDC Groups*

F_0 /a/	4.0-5.11y (2-3y of CI use)				6.0- 7.11y (3-4y of CI use)						
	Mean	SD	Median	IQR	Mean	SD	Median	IQR	|z|	*p*	*r*
CI	292	52	297	93	271	21	271	26	1.06	0.32	0.19
TDC	299	33	302	31	280	18	270	36	3.06	0.00**	0.43

Note. SD: standard deviation, IQR: interquartile range, *r*: effect size, y: years

**$p<0.01$,

Fundamental frequency of /a/ decreased with increase in period of implant use, but the difference was not statistically significant. In case of TDC, F_0 of /a/ decreased significantly (|z|=3.06, $p<0.01$, $r= 0.48$) with age. Mann Whitney U test was employed for group comparison and is provided in Table 4.29.

Table 4.29

Results of Mann Whitney U test for Comparison of F_0 of /a/ *in Children using CI and TDC in both Age Groups*

F_0 /a/	CI vs TDC (4.0-5.11 years)			CI vs TDC (6.0-7.11 years)		
	|z|	*p*	*r*	|z|	*p*	*r*
F_0 /a/	0.88	0.88	0.14	0.23	0.24	0.04

Note. r- effect size

As evidenced from table 4.29, the results of Mann Whitney U test revealed that F_0 of /a/ in children using CI was comparable to that of TDC ($p>0.05$) in both age groups. This finding suggests that children approximated the normal range of F_0 by 2 years of post-cochlear implantation.

4.1.2.1.2. Formant Frequencies (F_1 & F_2).

First and second (F_1 & F_2) formant frequencies were measured for word initial vowels (/a/, /i/, /u/, /e/ and /o/) from bisyllabic words. Vowel Space area was computed using the first two formant frequencies of the three corner vowels /a/, /i/ and /u/ using a MATLAB based program. The mean, standard deviation, median, and inter quartile range, |z|, *p* and *r* values of F_1, F_2 and VSA in children using CI and TDC were measured and are provided in Table 4.30 and 4.31 respectively.

Table 4.30

Mean, Standard Deviation, Median, Inter Quartile Range, |z|, *p and r Values of* F_1, F_2 *and VSA between Children with 2-3 and 3-4 years of CI Experience*

Parameter	4.0-5.11y (2-3y of CI use)				6.0- 7.11y (3-4y of CI use)						
	Mean	SD	Median	IQR	Mean	SD	Median	IQR	|z|	*p*	*r*
F_1 /a/	1083	218	1064	417	987	226	978	437	1.35	0.18	0.25
F_2 /a/	1901	245	1850	371	1697	184	1719	294	2.41	0.02	0.44
F_1 /i/	546	114	550	202	544	47	539	84	0.30	0.76	0.05
F_2 /i/	3311	202	3371	399	3263	325	3402	547	0.09	0.94	0.02
F_1 /u/	571	76	583	142	549	71	540	109	0.64	0.53	0.12
F_2 /u/	1084	141	1107	205	1076	242	1042	502	0.57	0.59	0.10

Parameter	4.0-5.11y (2-3y of CI use)				6.0- 7.11y (3-4y of CI use)						
	Mean	SD	Median	IQR	Mean	SD	Median	IQR	|z|	*p*	*r*
F_1 /e/	674	52	670	97	626	52	636	109	2.17	0.03	0.40
F_2/e/	3015	283	3096	568	3133	240	3009	459	1.01	0.33	0.18
F_1 /o/	668	73	692	153	720	99	704	167	1.45	0.15	0.26
F_2 /o/	1313	175	1290	242	1261	196	1217	355	0.85	0.40	0.16
VSA	574	266	595	366	449	246	392	439	1.20	0.24	0.22

Note. SD: standard deviation, IQR: interquartile range, *r*: effect size, y: years

Table 4.31

Mean, Standard Deviation, Median, Inter Quartile Range, |z|, p and r Values of F_1, F_2 and VSA between Age Groups in TDC Group

Parameter	4.0-5.11 years				6.0-7.11 years						
	Mean	SD	Median	IQR	Mean	SD	Median	IQR	|z|	*p*	*r*
F_1 /a/	945	255	892	347	952	273	889	324	0.12	0.9	0.02
F_2 /a/	1639	154	1662	284	1637	185	1566	320	0.18	0.86	0.03
F_1 /i/	527	52	534	74	485	90	496	131	1.92	0.05	0.27
F_2 /i/	3285	258	3336	258	3099	335	3096	568	2.04	0.04*	0.29
F_1 /u/	512	93	539	162	534	66	517	109	0.87	0.39	0.12
F_2 /u/	1019	122	1042	196	992	131	998	166	0.75	0.45	0.11
F_1 /e/	632	61	627	87	611	69	627	131	0.94	0.35	0.13
F_2/e/	2976	177	2943	230	2980	159	2943	207	0.05	0.96	0.01
F_1 /o/	666	91	670	142	683	113	648	76	0.24	0.81	0.03
F_2 /o/	1228	180	1195	317	1189	147	1151	241	0.74	0.46	0.10
VSA	555	323	460	499	492	281	410	556	0.65	0.52	0.09

Note. SD: standard deviation, IQR: interquartile range, *r*: effect size

*$p<0.05$

The formant frequencies F_1 and F_2 decreased with increase in implant use for most of the vowels studied. The only exception of this trend was the F_1 of mid back vowel /o/ and F_2 of high front vowel /i/, which increased with advance in implant use. However none of these changes in formant frequencies were statistically significant. Similarly a general trend of decrease in both first and second formant frequencies with increase in age was observed in TDC as well. However a significant reduction was noted only for F_2 of high front vowel /i/ ($|z|=2.04$, $p<0.05$, $r=0.32$). The pattern of formant frequencies was uniform in CI and TDC groups irrespective of age. As documented in the previous literature, the change in formant frequencies was as follows: F_1- /i/ < /u/ < /e/ < /o/ < /a/ and F_2- /u/ < /o/ < /a/ < /e/ < /i/

The vowel space area decreased with increase in implant age, though not statistically significant (p>0.05). Similarly, a non-significant reduction (p>0.05) in VSA with increase in age was noted in TDC as well. Mann Whitney U test was employed to analyze significant differences between the groups and the results are tabulated in Table 4.32.

Table 4.32

Results of Mann Whitney U Test for Comparison of F_1, F_2 and VSA in Children using CI and TDC in both Age Groups

Parameter	CI vs TDC (4.0-5.11 years)			CI vs TDC (6.0-7.11 years)		
	|z|	*p*	*r*	|z|	*p*	*r*
F_1 /a/	1.61	0.11	0.25	0.59	0.55	0.09
F_2 /a/	2.98	0.01*	0.47	0.93	0.36	0.15
F_1 /i/	1.81	0.07	0.29	1.00	0.32	0.16
F_2 /i/	0.12	0.90	0.02	1.55	0.12	0.25
F_1 /u/	1.45	0.15	0.23	1.18	0.24	0.19
F_2 /u/	1.50	0.14	0.24	0.66	0.51	0.10
F_1 /e/	2.01	0.06	0.32	0.69	0.49	0.11
F_2/e/	0.64	0.52	0.10	1.96	0.05	0.31
F_1 /o/	0.18	0.86	0.03	1.32	0.19	0.21
F_2 /o/	1.33	0.18	0.21	1.12	0.27	0.18
VSA	0.91	0.36	0.14	1.09	0.28	0.17

Note. r: effect size

*p<0.05

The first and second formants of the five vowels in children using CI did not significantly differ from TDC except F_2 /a/ in the younger age group. F_2 /a/ was significantly higher (|z|=2.98, p<0.05, r=0.47) in children using CI than that of TDC. On observation, it was noted that the F_1 and F_2 of other vowels were also higher in CI compared to TDC though the difference was non-significant (*p*>0.05). VSA in CI was comparable to that of TDC, although children with CI exhibited slightly higher VSA in younger age group and lower in older age group compared to TDC.

4.1.2.2. Nasals.

Nasal murmur was analyzed for bilabial /m/, dental /n̪/, and palatal /ɲ/ nasals in the word initial position. The mean, standard deviation, median, and inter quartile range, |*z*|, *p* and *r* values of nasal murmur in CI and TDC groups between age are provided in Table 4.33 and Table 4.34 respectively.

Table 4.33

Mean, Standard Deviation, Median, Inter Quartile Range, |z|, p and r Values of Nasal Murmur (NM) between 2-3 and 3-4 years of CI Experience

Nasal Murmur	4.0-5.11y (2-3y of CI use)				6.0- 7.11y (3-4y of CI use)						
	Mean	SD	Median	IQR	Mean	SD	Median	IQR	|z|	*p*	*r*
/m/	411	68	390	29.5	376	40	386	43	1.65	0.09	0.30
/n̪/	493	86	495	171.5	479	62	474	110	0.55	0.58	0.10
/ɲ/	485	72	496	96	459	76	477	159	0.54	0.58	0.10

Note. SD: standard deviation, IQR: interquartile range, y: years

Table 4.34

Mean, Standard Deviation, Median, Inter Quartile Range, |z|, p and r Values of Nasal Murmur (NM) between Age Groups in TDC Group

Nasal Murmur	4.0-5.11 years				6.0-7.11 years						
	Mean	SD	Median	IQR	Mean	SD	Median	IQR	|z|	*p*	*r*
/m/	384	48	386	82	362	53	364	82	1.52	0.12	0.21
/n̪/	472	60	479	87	443	51	436	87	1.65	0.09	0.23
/ɲ/	475	59	487	120	476	58	473	91	0.50	0.61	0.07

Note. SD: standard deviation, IQR: interquartile range, *r*: effect size

As observed from Table 4.33, nasal murmur decreased with increase in CI experience. Similarly, an age dependent decrease in NM was manifested in TDC as indicated in Table 4.34. However, there was no significant difference noted between age groups in both groups. NM exhibited similar pattern with respect to place of articulation in both the groups. It was found to decrease as the place of articulation moved forward. i.e. palatal /ɲ/ > dental /n̪/ > bilabial /m/. Results of Mann Whitney U test of nasal murmur is provided in Table 4.35.

Table 4.35

Results of Mann Whitney U Test for Comparison of Nasal Murmur in Children using CI and TDC in both Age Groups

Nasal Murmur	CI vs TDC (4.0-5.11 years)			CI vs TDC (6.0-7.11 years)		
	|z|	*p*	*r*	|z|	*p*	*r*
/m/	0.88	0.37	0.14	0.98	0.32	0.15
/n̪/	0.74	0.45	0.12	1.78	0.07	0.28
/ɲ/	0.53	0.59	0.08	0.72	0.47	0.11

Note. r: effect size

The results of the Mann Whitney U test indicated that none of the nasal consonants showed significant difference (*p*>0.05) between groups. However, NM was observed to be higher in CI group compared to TDC in both age groups.

4.1.3. Summary of Findings of Acoustic Parameters

4.1.3.1. Temporal Measures.

Vowel Duration: Marginal reduction in VD (non-significant) was observed with increase in duration of implant use. Irrespective of the duration of implant use, children using CI exhibited significant lengthening of vowels compared to TDC.

Ratio of Duration of Long and Short Vowels: The ratio of duration of long and short vowels was observed to decrease with implant age though the difference was non-significant. Compared to TDC, a higher ratio was noted for all vowels with a significantly higher ratio demonstrated for vowel /a/. Further, the highest value of ratio of duration of long vowels was thrice as long as the short vowel in CI.

Voice Onset Time: A general trend of reduction in VOT was observed with advance in duration of implant use for most of the phonemes. VOT of most of the phonemes approached normal limits. However, dental and retroflex stops exhibited a significant difference in younger (/ɖ/, /t/) and older (/ɖ/, /d/) group of CI compared to TDC.

Burst Duration: BD of all phonemes decreased with increase in CI experience with a significant reduction noticed for retroflex /ɖ/. It was the longest for velars and the shortest for bilabials for both unvoiced and voiced stops in both CI and TDC groups. BD of most of the phonemes in children using CI approached normal values except for dental /d/, retroflex /ɖ/ and velar /k/.

Closure Duration: A significant decrease in CD with advance in implant use was noted for retroflex /ʈ/ and velar /g/. However, CD of most of the phonemes remained unchanged even after 3-4 years of implant experience. CD was found to be significantly longer in children using CI for most of the phonemes irrespective of age. It was noted that among the temporal parameters of stops investigated in the present study, CD is one of the most affected measure in children using CI.

Nasal Consonant Duration: Considerable reduction in NCD with increase in implant use was observed for most of the nasal phonemes with a significant reduction noted for alveolar /n/ and retroflex /ɳ/. However, NCD of nasals were significantly longer compared to TDC except for alveolar /n/ and velar /ŋ/.

Frication Duration: An overall reduction in FD with increase in implant experience was observed for all fricatives. Notably, FD of all phonemes in the older CI group approached normal limits. It can be concluded that there was a substantial improvement in FD with increase in implant experience.

Affrication Duration: Affrication duration of voiced /ɟ/ was significantly longer in the younger CI group, although unvoiced /c/ showed similar values to that of

TDC. In the older group of children using CI, AD of both affricates approached towards typical values.

Word Duration: Word duration was found to decrease with increase in implant experience with a significantly longer duration for words with short vowels /e/ and /o/. WD was found to be significantly longer in younger and older groups of children using CI compared to TDC.

4.1.3.2. Spectral measures.

Fundamental Frequency: F_0 /a/ in children using CI was comparable to that of TDC in both younger and older age groups.

Formants: F_1 and F_2 of most of the vowels reduced (non-significant) with increase in implant use for most of the vowels studied. The formant frequencies of vowels in children using CI were comparable to TDC except for F_2 /a/ which was significantly higher in CI.

VSA: The vowel space area in children using CI was comparable to TDC.

Nasal murmur: Nasal murmur decreased with increase in CI experience. Interestingly, nasal murmur of all nasals was comparable to TDC in both subgroups of CI.

The present study also indicated that there was no significant difference between gender for the acoustic measures studied in children using CI and TDC. Also there was high variability in the acoustic measures in both CI and TDC group with a higher variability in the former group. However, there was no steady and gradual reduction in variability of acoustic measures with increase in age. Overall it could be observed that spectral measures approached normal limits even in children with lesser CI experience. However, the temporal measures were significantly affected in both subgroups of CI.

4.2. Articulatory Characteristics of Speech in Children using CI and TDC

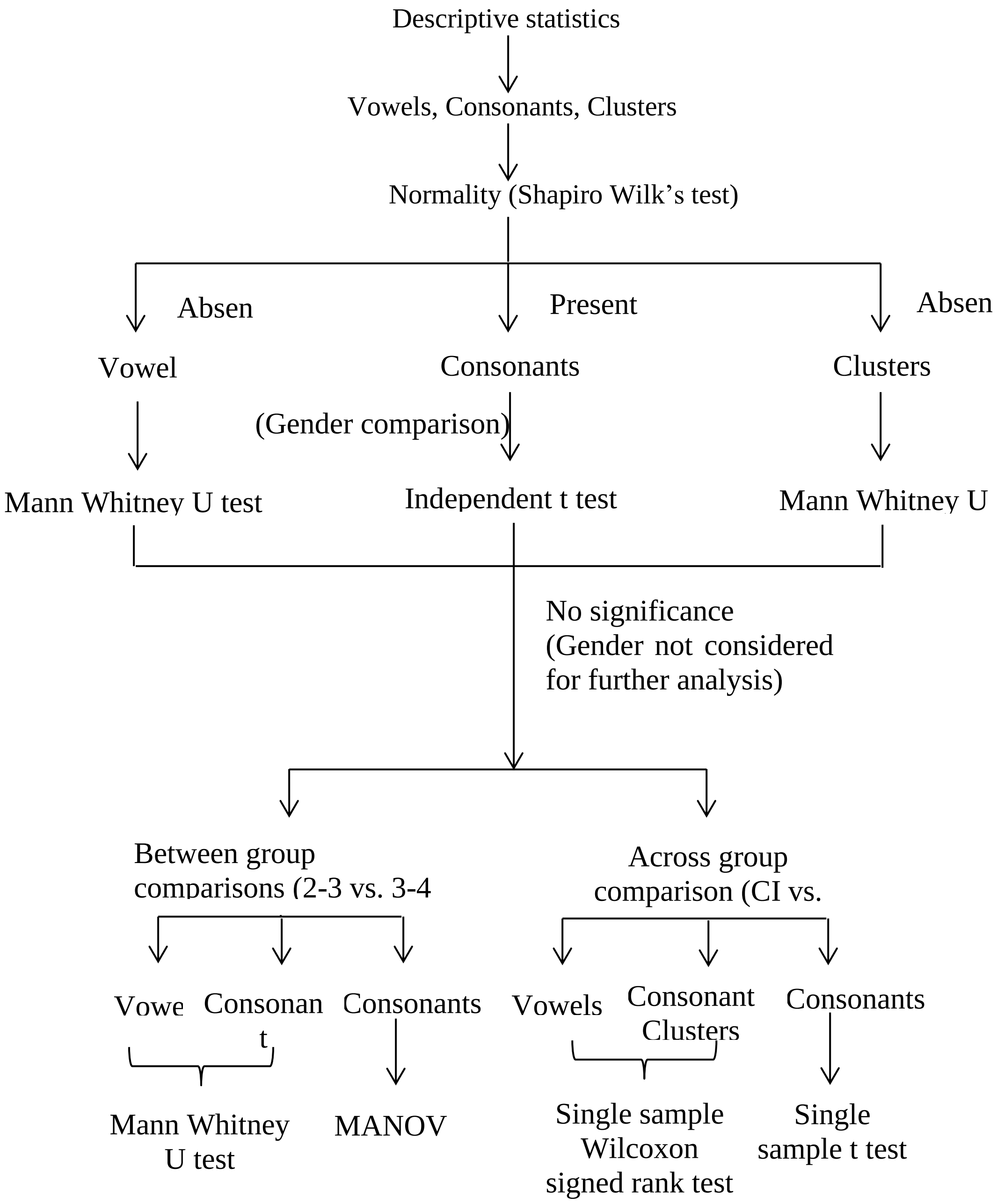
Malayalam diagnostic articulation test-revised was administered to test the articulatory skills of participants. The audio recordings of participants were transcribed using the Malayalam phonetic chart provided by Kavya Manohar (2020) and was subjected to articulatory analysis. Vowels, consonants and consonant clusters were quantitatively and qualitatively analyzed and profiled.

For quantitative analysis of vowels, consonants and consonant clusters, percentage of vowels correct (PVC), percentage of consonants correct-R (PCC-R) and Percentage of consonant clusters correct (PCCC) were calculated. These measures were subjected to statistical analyses using SPSS (Statistical Package for Social Science) version 21. Normality of the data was tested using Shapiro Wilk's test of normality. Results of normality test indicated that the data distribution was non-normal ($p<0.05$) in TDC. Therefore, a median score of 100 (constant) was considered as there were no articulatory errors for both age groups of TDC. In CI group, the data was normally distributed for consonants ($p>0.05$) and non- normal distribution for vowels and consonant clusters ($p<0.05$). Hence parametric tests were used for consonants and non-parametric tests for vowels and consonant clusters for statistical comparisons across age groups in CI.A flowchart of statistical analyses performed on articulatory measures of speech is depicted in Figure 4.16.

Gender wise comparisons carried out using independent t test for consonants and Mann -Whitney U test for vowels and consonant clusters revealed that the data did not show significant gender differences ($p>0.05$). Hence gender was not considered for further statistical analyses.

Figure 4.16

Flowchart of Statistical Analyses Performed on Articulatory Measures



Statistical comparisons were carried out only for quantitative measures. Mann-Whitney U test was used for between age group comparisons of vowels and consonant clusters and Multivariate analysis of variance (MANOVA) for consonants in children using CI. MANOVA was employed for age comparisons within CI group. As the median values of both sub groups of TDC was 100 (all correct productions with no articulatory errors) between age group comparisons were not carried out. Across group comparisons (CI vs TDC) were done using single sample Wilcoxon signed rank test for vowels and clusters (as TDC had constant median value 100) and single sample t- test (as mean= median= 100) for consonants.

Qualitative analysis of vowels was carried out to identify the vowel errors. The consonant errors were profiled qualitatively using SODA and PMV analyses. Consonant clusters were analyzed to identify the predominant error patterns including cluster simplifications, cluster reductions and cluster omissions.

4.2.1. Vowels

Vowels considered for articulatory analyses include low-central vowel /a/, high-front vowel /i/, high-back vowel /u/, mid-front vowel /e/, mid-back vowel /o/ and mid-central vowel /ə/. MAT-R tests for vowels only in word initial position. Hence for detailed analysis, vowels in all words were considered and were listed separately with respect to phoneme position (initial, medial, & final). The vowel productions of the participants were subjected to quantitative and qualitative analyses and are discussed separately. Accuracy of vowel production was measured quantitatively using percentage of vowels correct (PVC).

4.2.1.1. Percentage of Vowel Correct (PVC).

Percentage of vowel correct (PVC) was calculated for all six vowels in initial, medial and final positions based on their occurrence in respective positions in the language. Results of normality test revealed that the data followed non-normal distribution. Hence, Mann- Whitney U test was employed for comparing PVC scores between the subgroups in children using CI (2-3 vs 3-4 years of CI use). Comparison between age groups in TDC was not carried out as there were no vowel errors in this group. Vowel errors were classified as substitution, omission and addition errors and substitution errors were further classified based on the vowels substituted with. Mean, standard deviation, median and inter quartile range, |z|, *p* and *r* values of PVC in children using CI was measured and are provided in Table 4.36.

Table 4.36

Mean, Standard Deviation, Median, Inter Quartile Range, |z|, *p* and *r* Values *of PVC between Children with 2-3 and 3-4 years of CI Experience*

PVC	4.0-5.11y (2-3y of CI use)				6.0-7.11y (3-4y of CI use)						
	Mean	SD	Median	IQR	Mean	SD	Median	IQR	|z|	*p*	*r*
Initial	86.67	10.39	86.67	13.33	94.22	7.07	93.33	6.67	2.22	0.03*	0.41
Medial	93.07	6.23	96.00	8.00	97.07	2.25	98.00	2.00	2.11	0.04*	0.39
Final	98.16	2.26	97.87	2.13	99.15	1.08	100.00	2.13	1.33	0.19	0.24
Total	94.35	4.26	94.64	2.68	97.56	1.70	97.32	2.68	2.78	0.01*	0.51

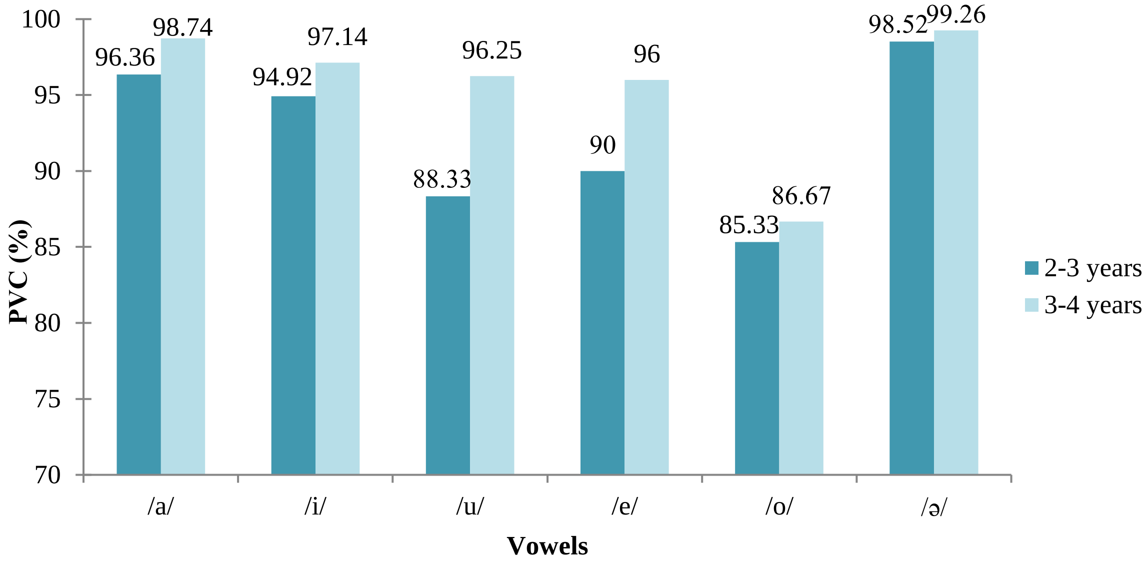
Note. PVC- percentage of vowel correct, SD-standard deviation, IQR-inter quartile range, r-effect size

*$p<0.05$

Vowel errors were less in children using CI as indicated by the PVC scores nearing 100% in both younger and older group of children using CI. PVC scores were found to increase with increase in implant experience with a significant increase noted only in initial (|z|=2.22, $p<0.05$, $r=0.41$) and medial positions (|z|=2.11, $p<0.05$, $r=0.39$). Errors in initial position were predominantly consonant additions in the prevocalic position (for e.g. /konnə/ for /onnə/) where the vowel production was correct and other errors were negligible. PVC scores in initial position were greater than 98% when addition errors were excluded making it the most accurate position. Statistical comparisons across positions were not carried out as there were differences in the number of target words present in different phoneme positions. For e.g. the number of vowels tested in the initial was less compared to other places. Comparison of PVC scores of six vowels between two sub groups of children using CI is depicted in Figure 4.17.

Figure 4.17

Comparison of PVC Scores of Vowels in Children with 2-3 and 3-4 years of CI Experience



Accuracy of production for most of the vowels analyzed were greater than 90% in both subgroups of CI. The highest scores were observed for mid central vowel /ə/ in both younger (98.52%) and older (99.26%) groups of CI. Notably, back vowels /u/ and /o/ had the least accuracy with in both groups. The accuracy of mid-back vowel /o/ was considerably less with minimal improvement (85.33% to 86.67%) noticed with increase in duration of implant experience. The overall trend of production difficulty in CI was noted to be similar in both subgroups and the decreasing order of accuracy scores are as follows: /ə/ > /a/ > /i/> /e/ > /u/ > /o/.

PVC scores of clinical group and TDC were compared using single sample Wilcoxon test as vowel errors were absent in TDC and their median values were 100. The results of single sample Wilcoxon signed rank test is shown in Table 4.37. The table below for across group comparisons is represented with respect to the chronological age of the participants. It has to be noted that the participants in younger group (4.0-5.11 years) of CI were with 2-3 years of CI experience and older group (6.0-7.11 years) of CI were with 3-4 years of CI use. The results indicated that the PVC scores of children using CI were significantly lower compared to TDC in both medial ($p<0.01$) and final ($p<0.05$) positions. However, there was no significant difference for initial position between CI and TDC.

Table 4.37

Results of Single Sample Wilcoxon Signed Rank Test for Comparison of PVC between CI and TDC Groups

PVC	CI vs TDC (4.0-5.11 years)	CI vs TDC (6.0-7.11 years)
	p	*p*
Initial	0.18	1.00
Medial	0.00**	0.00**
Final	0.01*	0.02*
Total	0.00**	0.00**

Note. PVC- percentage of vowels correct

*$p<0.05$, **$p<0.01$

4.2.1.2. Qualitative Analysis of Vowel Errors.

For qualitative analysis, vowel errors were classified into substitution, omission and addition errors in initial, medial and final positions and are as shown in Table 4.38. Omission errors were observed in negligible percentage (<2%) in all positions and was observed only for low-central vowel /a/ and high-back vowel /i/. Addition errors were observed predominantly in initial position and the target vowel was produced correctly in spite of addition errors. Substitution errors constituted the major percentage of errors in medial position whereas it was observed in negligible percentage in initial and final positions. As there were no vowel errors in TDC the data is not represented. The findings of children using CI are represented with respect to the duration of CI use (2-3 & 3-4 years)

Table 4.38

Percentage of Substitution, Omission and Addition Errors of Vowels across Position in Children with 2-3 and 3-4 years of CI Experience

Position	Implant experience	Substitution (%)	Omission (%)	Addition (%)
Initial	2-3 years	0.88	-	12.44
	3-4 years	-	-	5.33
Medial	2-3 years	5.35	1.60	-
	3-4 years	2.13	0.80	-
Final	2-3 years	0.56	0.85	0.70
	3-4 years	0.71	-	0.28

Vowel substitution errors were analyzed in detail. A confusion matrix was constructed including the percentage of correct productions and substitutions with other vowels. Vowels were not analyzed separately in terms of length (i.e. short and long vowels were combined) and vowel position as the substitution pattern did not vary with these parameters. Confusion matrix of substitution errors of vowels in both subgroups of children using CI is shown in Table 4.39 and Table 4.40

From the table it could be noted that overall reduction in substitutions and variability of errors were noticed with increase in implant experience. Substitution with mid central vowel /ə/ was common in children with lesser CI experience. Such errors were completely absent in children with longer implant experience (3-4 years) indicating a reduction in vowel centralization with increase in implant experience. With increase in implant experience, substitutions with more proximal vowels were observed. For example, in younger group of children, /u/ was substituted with /ə/ and /i/ and in older group it was with /o/.

Table 4.39

Confusion Matrix for Vowel Substitution Errors (in Percentage) in Children using CI with 2-3 years of Implant Experience

		Vowel produced					
		/a/	/i/	/u/	/e/	/o/	/ə/
Target vowel	/a/	**97.36**	0.18	-	0.28	0.38	1.80
	/i/	-	**96.92**	-	1.95	-	1.13
	/u/	-	3.83	**91.33**	-	-	4.84
	/e/	0.67	3.33	2.00	**92.67**	-	1.33
	/o/	3.97	-	6.70	-	**89.33**	-
	/ə/	1.41	-	-	-	-	**98.59**

Note. Percentages of correct productions are in bold

Table 4.40

Confusion Matrix for Vowel Substitution Errors (in Percentage) in Children using CI with 3-4 years of Implant Experience

		Vowel produced					
		/a/	/i/	/u/	/e/	/o/	/ə/
Target vowel	/a/	**98.74**	0.77	-	-	0.49	-
	/i/	1.32	**97.85**	-	0.83	-	-
	/u/	-	-	**96.25**	-	3.75	-
	/e/	1.67	2.33	-	**96**	-	-
	/o/	2.67	-	4.67	-	**92.66**	-
	/ə/	0.74	-	-	-	-	**99.26**

Note. Percentages of correct productions are in bold

As observed from PVC scores, back vowels were the most difficult and /ə/ was the most accurate vowel. Among front vowels, high vowel /i/ was predominantly substituted with mid vowel /e/ and vice versa in both groups of CI indicating confusions in tongue height. Similar to front vowels, tongue height confusions were seen among back vowels also. /u/ was frequently substituted with /o/ and vice versa. Such substitutions observed among front and back vowels can be considered as a more developmentally appropriate error pattern. Mid-central vowel /ə/ was substituted only with low-central vowel /a/ in both sub groups of CI. Errors in tongue advancement were noted in younger group of participants. For e.g., mid- front vowel /e/ was substituted with high- back vowel /u/ and high- front vowel /i/ with mid-central vowel /ə/ and low-central vowel /a/. However, the percentage of such substitution errors was minimal.

To conclude, vowel errors were less in children using CI and was found to decrease with increase in implant experience. From the analysis of vowel errors it was noticed that omission errors were less compared to other errors. Addition errors were observed predominantly in initial position and the target vowel was produced correctly in spite of addition errors. Substitution errors constituted the major percentage of errors in medial position whereas it was observed in negligible percentage in initial and final positions. Tongue height confusions were predominant than tongue advancement errors. Substitution with mid-central vowel /ə/ was common in children with lesser implant experience, whereas it was absent in the older group. With increase in implant experience, substitutions with more proximal vowels were observed.

4.2.2. Consonants

The consonant productions of the participants were subjected to quantitative and qualitative analyses similar to vowels. The accuracy of consonant production was documented using percentage of consonants correct- revised (PCC-R) with respect to places and manners of articulation and was subjected to statistical analysis. The consonant errors were profiled qualitatively using SODA and PMV analyses. The results will be discussed under the following headings:

4.2.2.1.Quantitative analysis (PCC-R)

4.2.2.2. Qualitative analyses

- SODA
- PMV

4.2.2.1. Quantitative Analysis (PCC-R)

PCC-R was calculated separately for various places and manners of articulation considering all words of MAT-R (see method section 3.4.3.2.2). Places of articulation discussed include bilabials, labiodentals, dentals, alveolars, retroflex, palatals, velars and glottals. Manners of articulation discussed include four sections namely: stops, nasals, fricatives/affricates, and approximants (glides, laterals, trills, flaps, and approximant /z̢/). Further, an attempt was made to compare PCC-R scores across phoneme positions in different manners of articulation. Statistical comparisons across positions were not carried out due to wide disparity in the number of target words present in different phoneme positions. Also detailed position wise analysis was carried out and is provided in qualitative analysis. In TDC group, PCC-R scores were close to 100% for almost all participants as there were only minimal articulatory errors. Hence the scores are not represented in the tables below.

4.2.2.1.1. Place of Articulation.

PCC-R was computed for seven places of articulation for clinical and control groups. The results of Shapiro Wilk’s test of normality revealed that the data was normally distributed. Therefore, the parametric test MANOVA was employed to compare the scores between two groups of children using CI with varying implant experience. Comparisons between age groups were not carried out for TDC as there were no misarticulations. Mean, standard deviation of PCC-R and results of MANOVA are shown in table 4.41. PCC-R scores of two sub groups of CI (2-3 & 3-4 years of CI experience) across various places of articulation are graphically represented in Figure 4.18. From the Table 4.41 and Figure 4.18, it could be observed that the scores improved with increase in implant experience, however a significant increase was noted only in bilabials (F (1, 14) = 4.73, $p<0.05$, Wilk's $\wedge=0.78$, partial $\eta^2=0.06$). Also, PCC-R scores were the highest for bilabials and the lowest for retroflex in both subgroups of CI. Similar to retroflex, other places which had poor scores were dentals and alveolars.

Table 4.41

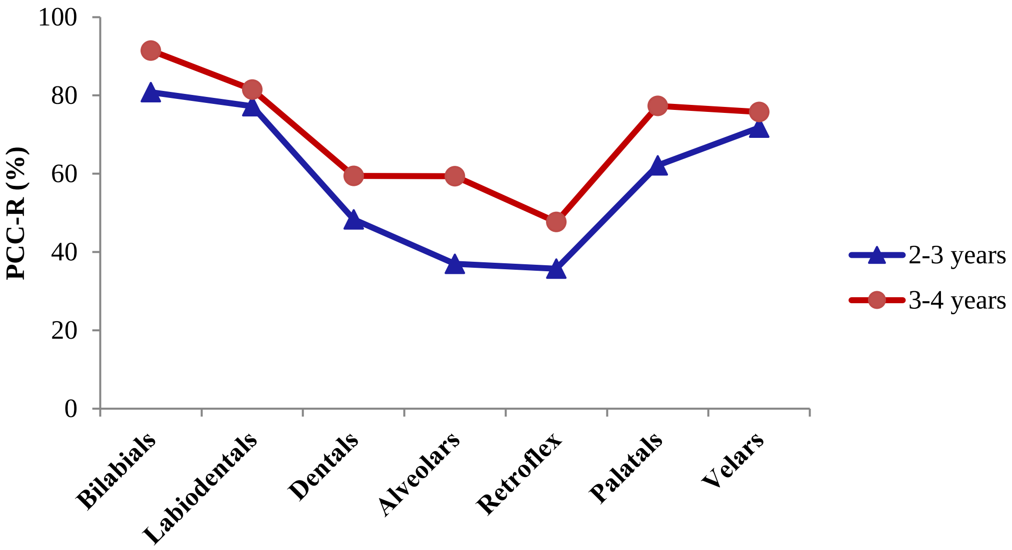
Mean, Standard Deviation of PCC-R and Results of MANOVA across Places of Articulation in Children with 2-3 and 3-4 years of CI Experience

POA	2-3 years		3-4 years		F (1,14)	*p*	Partial η^2
	Mean	SD	Mean	SD			
Bilabials	80.83	8.00	91.49	4.25	4.73	0.03*	0.06
Labiodentals	77.27	15.15	81.54	12.27	0.30	0.59	0.00
Dentals	48.33	19.86	59.44	15.71	0.55	0.46	0.01
Alveolars	36.99	11.32	59.38	14.47	2.02	0.16	0.03
Retroflex	35.75	15.26	47.69	11.70	0.99	0.32	0.01
Palatals	62.14	12.60	77.33	5.38	2.42	0.12	0.03
Velars & glottals	71.76	10.94	75.76	24.46	0.15	0.70	0.00

Note. POA-place of articulation, SD-standard deviation, (df)-degrees of freedom

Figure 4.18

PCC-R Scores across Various Places of Articulation in Children with 2-3 and 3-4 years of CI Experience



Results of single sample t- test for across group comparisons of PCC-R scores of CI and TDC groups are provided in Table 4.42. Across group comparisons between CI and TDC are represented with respect to the chronological age of the participants. It has to be noted that the participants in younger group (4.0-5.11 years) of CI were with 2-3 years of CI experience and older group (6.0-7.11 years) of CI were with 3-4 years of CI use. PCC-R scores were significantly poorer for all places of articulation for both sub groups of CI compared to TDC ($p<0.01$).

Table 4.42

Results of Single Sample t test for between Group Comparison of PCC-R across Places of Articulation in Children using CI and TDC

POA	CI vs TDC (4.0-5.11 years)		CI vs TDC (6.0-7.11 years)	
	t(14)	*p*	t(14)	*p*
Bilabials	9.28	0.00**	7.75	0.00**

POA	CI vs TDC (4.0-5.11 years)		CI vs TDC (6.0-7.11 years)	
	t(14)	*p*	t(14)	*p*
Labiodentals	5.81	0.00**	5.83	0.00**
Dentals	10.08	0.00**	10.00	0.00**
Alveolars	21.56	0.00**	10.87	0.00**
Retroflex	16.31	0.00**	17.31	0.00**
Palatals	11.63	0.00**	16.32	0.00**
Velars & glottals	3.84	0.00**	10.00	0.00**

Note. POA-place of articulation,

***p*<0.01

4.2.2.1.2. Manner of Articulation.

PCC-R was calculated for various manners of articulation in initial, medial and final positions. Within group comparison of PCC-R in subgroups of CI was carried out using MANOVA. Mean, standard deviation of PCC-R and results of MANOVA are shown in Table 4.43. PCC-R scores of two subgroups of CI across various manners of articulation are shown in Figure 4.19 and Figure 4.20. It could be noted that PCC-R scores increased with increase in implant experience for all manners of articulation with a significant improvement noted only for nasals in initial [F (1, 14) =9.06, p<0.00, Wilk's $\wedge$=0.73, partial η^2=0.10 and final ([F (1,14) = 8.21, p<0.05, partial η^2=0.09) position. Nasals had the highest PCC-R scores and approximants had the lowest, irrespective of implant experience. Scores of approximants did not have considerable improvement even after 3-4 years of implant experience. The decreasing order of PCC-R scores in both sub groups of CI was as follows: nasals>stops>fricatives and affricates >approximants. With respect to phoneme position, PCC-R values were better in initial position for stops and nasals whereas it was in medial position for fricatives, affricates and approximants.

Table 4.43

Mean, Standard Deviation of PCC-R and Results of MANOVA across Manners of Articulation in Children with 2-3 and 3-4 years of CI Experience

MOA	Phoneme position	2-3 years		3-4 years		F(1,14)	p	Partial η^2
		Mean	SD	Mean	SD			
Stops	Initial	65.97	15.04	73.08	9.53	0.65	0.42	0.01
	Medial	54.07	13.19	65.13	8.90	0.77	0.38	0.01
Nasals	Initial	69.17	14.07	92.22	6.66	9.06	0.00**	0.10
	Medial	56.11	13.16	70.48	8.90	1.52	0.22	0.01
	Final	55.40	18.02	86.43	7.54	8.21	0.01*	0.09
Fricatives & affricates	Initial	51.52	16.72	67.50	14.98	1.48	0.22	0.02
	Medial	55.13	18.25	69.05	11.02	1.89	0.17	0.02
Approximants	Initial	28.67	20.31	45.00	20.61	0.91	0.34	0.01
	Medial	37.45	28.40	53.71	27.85	0.73	0.39	0.01
	Final	21.82	17.11	35.15	35.35	0.33	0.56	0.01

Note. MOA-manner of articulation, SD-standard deviation

*$p<0.05$

Figure 4.19

PCC-R Scores across Various Manners of Articulation in Children with 2-3 years of CI Experience

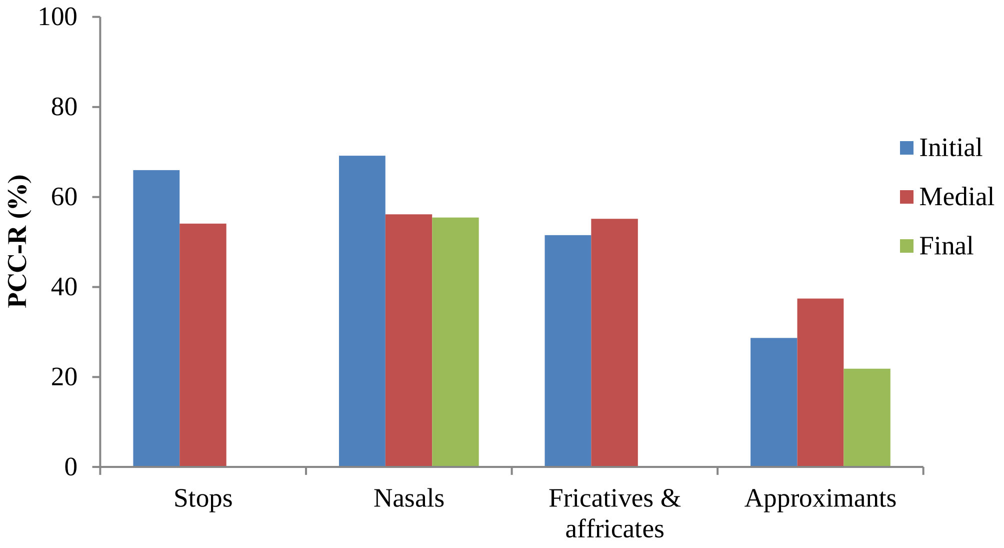
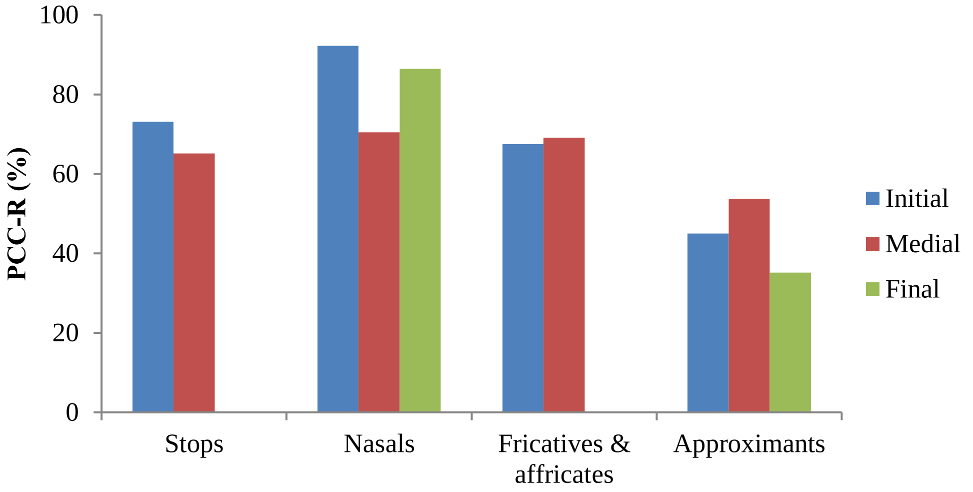


Figure 4.20

PCC-R Scores across Various Manners of Articulation in Children with 3-4 years of CI Experience



The results of single sample t- test for between group comparisons of PCC-R scores of CI and TDC groups are provided in Table 4.44. The table below for across group comparisons is represented with respect to the chronological age of the participants. PCC-R scores were significantly poorer for all manners of articulation for both sub groups of CI compared to TDC (*p*<0.01).

Table 4.44

Results of Single Sample t Test for Between Group Comparison of PCC-R Scores across Manners of Articulation in Children using CI and TDC

MOA	Position	CI vs TDC (4.0-5.11 years)		CI vs TDC (6.0-7.11 years)	
		t(14)	*p*	t(14)	*p*
Stops	Initial	8.76	0.00**	10.94	0.00**
	Medial	13.48	0.00**	15.18	0.00**
Nasals	Initial	8.49	0.00**	4.53	0.00**
	Medial	12.91	0.00**	12.85	0.00**
	Final	9.59	0.00**	6.97	0.00**
Fricatives & affricates	Initial	11.23	0.00**	8.40	0.00**
	Medial	9.52	0.00**	10.88	0.00**
Approximants	Initial	13.60	0.00**	10.34	0.00**
	Medial	8.53	0.00**	6.44	0.00**
	Final	17.70	0.00**	7.10	0.00**

Note. MOA- place of articulation, ***p*<0.01

To summarize, PCC-R scores increased with increase in implant experience for all places and manners of articulation. However significant improvement was noted only for bilabials and nasals (medial position) (*p*<0.05). Scores were significantly poorer for all places and manners of articulation in children using CI compared to TDC (*p*<0.01). Among places of articulation, bilabials had the highest PCC-R scores and retroflex had the lowest in both sub groups of CI. Among manners, nasals were the most accurate and approximants were the least accurate in both sub groups of CI. PCC-R scores were better in initial position for stops and nasals and in medial position for fricatives, affricates and approximants.

4.2.2.1. Qualitative Analysis.

SODA and PMV analysis were employed for qualitative profiling of consonant errors. An attempt was made to document the same across phoneme positions (initial, medial & final). Percentage of participants exhibiting substitution, omission, distortion and addition errors was calculated. Substitution errors identified through SODA analysis was further subjected to PMV analysis. Changes in error profile with an increase in implant experience were also examined. The results of qualitative analyses will be discussed separately in the following sections with respect to place, manner and voicing to identify error patterns of the respective categories.

The scores of TDC are not represented in tables as there were no articulatory errors in the participants. The subgroups of CI represented are as follows, Subgroup I (younger group) consisted of participants with 2-3years of CI use and subgroup II (older group) with 3-4 years of CI use.

4.2.2.2.1. Errors of Place of Articulation.

Consonants were grouped under seven places of articulation similar to quantitative analysis. Percentage of participants exhibiting SODA errors was tabulated under respective places of articulation. Substitution pattern analysis with respect to place of articulation was also tabulated in a similar manner i.e. in PMV feature analysis. The results of this section are represented under each POA.

1. Bilabials.

Four bilabial phonemes were tested which include /p/, /b/, /b^h/ and /m/. /p/ and /b/ were tested in initial and medial positions and nasal /m/ was tested in initial, medial, and final positions. Voiced aspirated stop /b^h/ was tested only in the initial position for older group of participants owing to its late age of acquisition.

SODA Analysis: Results of SODA analysis of bilabial phonemes in both sub groups of CI are shown in Table 4.45. Among bilabials, /m/ was the most correctly produced and /b/, the least correctly produced phoneme by participants in both the sub groups of CI. Voiced aspirated stop /b^h/ had exceptionally poor production (20%)

compared to its unaspirated cognate (60%). With increase in implant use, greater percentage of participants produced the phonemes correctly in all phoneme positions and the same is graphically represented in Figure 4.21. Substitutions were the most common error pattern exhibited in both phoneme positions by the participants irrespective of implant experience. The only exception to this trend was /p/, where omissions (33.33%) were the most frequent error pattern in the word initial position for younger group of participants.

Table 4.45

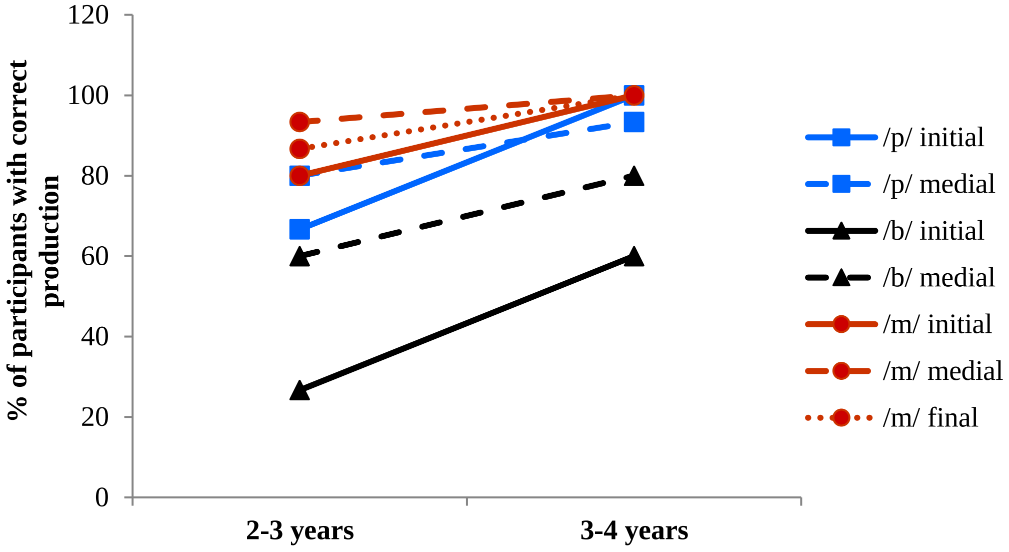
Percentage of Participants Exhibiting SODA Errors for Bilabials across Phoneme Position in Children with 2-3 and 3-4 years of CI Experience

Phoneme	Initial				Medial				Final			
	2-3 years		3-4 years		2-3 years		3-4 years		2-3 years		3-4 years	
	CR (%)	Err (%)	CR (%)	Err (%)	CR (%)	Err (%)	CR (%)	Err (%)	CR (%)	Err (%)	CR (%)	Err (%)
/p/	66.66	33.33 (O)	100	0	80	20 (S)	93.33	6.66 (S)	NT		NT	
/b/	26.66	66.66 (S) 6.66 (D)	60	40 (S)	60	40 (S)	80	20 (S)	NT		NT	
/b^h/	NT		20	80 (S)	NT		NT		NT		NT	
/m/	86.66	13.33 (S)	100	0	93.33	6.66 (0)	100	0	86.66	13.33 (0)	100	-

Note. CR: correct responses, Err: error, S-substitution O- Omission D- Distortion A-Addition, NT-not tested

Figure 4.21

Percentage of Participants with Correct Production of Bilabials in all Phoneme Positions with 2-3 and 3-4 years of CI Experience



Substitution Error Analysis: Substitution errors of bilabials were analyzed in terms of place of articulation and the detailed findings for each phoneme across phoneme positions are shown in Table 4.46. Substitution errors were absent for /p/ in initial position and /m/ in final position. In participants with lesser implant experience, bilabials were substituted with other bilabials, labiodentals, retroflexes and velars. As implant experience of participants increased, variability in class of phonemes with which the phoneme was substituted reduced to bilabials, labiodentals and dentals. Percentage of participants with correct production and substitution errors of bilabials in subgroups of CI is summarized and is shown in Figure 4.22. Percentage of correct production of bilabials increased from 77.31% to 81.66% with increase in duration of CI use. Percentage of substitutions with same place of articulation (i.e. bilabials) increased from 12.38% to 15% in children with longer implant experience compared to those with lesser CI experience.

Table 4.46

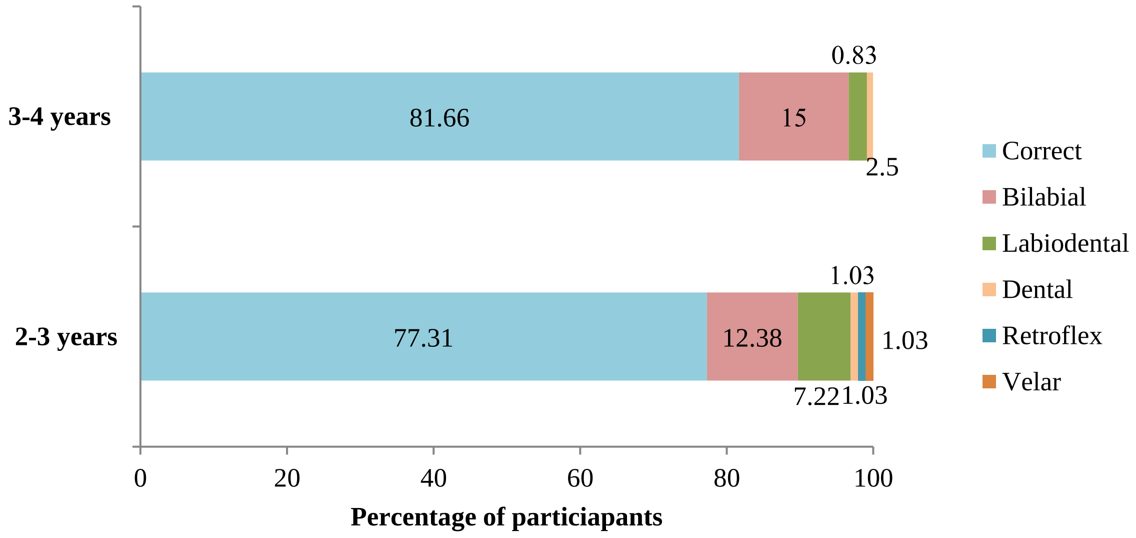
Substitution Errors of Bilabials in Children with 2-3 and 3-4 years of CI Experience

		2-3 years				3-4 years			
		NPS	PS	POA	PPS (%)	NPS	PS	POA	PPS (%)
/p/	I	0	-	-	-	0	-	-	
	M	3	/t/ /v/ /ɖ/	Dental Labiodental Retroflex	33.33 33.33 33.33	1	/t/	Dental	100
/b/	I	10	/p/ /v/,/f/	Bilabial Labiodental	80 20	6	/p/,/m/	Bilabial	100
	M	6	/p/ /f/,/v/	Bilabial Labiodental	66.66 33.33	3	/p/	Bilabial	100
/bʰ/	I	-	-	-	-	12	/p/ /v/	Bilabial Labiodental	75 25
/m/	I	2	/v/	Labiodental	100	0	-	-	-
	M	1	/ŋ/	Velar	100	0	-	-	-
	F	0	-	-		0	-	-	-

Note. NPS-Number of participants with substitution error, PPS(%)- Percentage of participants with substitution error, PS- phonemes substituted with, POA- place of articulation, I- initial, M- medial, F-final

Figure 4.22

Percentage of Participants with Correct Production and Substitution Errors of Bilabials in Children with 2-3 and 3-4 years of CI Experience



2. Labiodentals.

Labiodental phonemes analyzed in the study include /f/ and /v/. Among these phonemes, /f/ was tested in initial position only.

SODA Analysis: Results of SODA analysis of labiodental phonemes in both sub groups of CI are shown in Table 4.47. In participants with lesser CI experience, majority of participants produced /v/ more correctly compared to /f/, whereas those with longer CI experience had comparable scores for /f/ and /v/. The accuracy of /v/ was found to be higher in medial position (80%) compared to initial position (60%) in older group of participants, whereas it was similar for younger group. Comparison of percentage of correct production of labiodentals between children with 2-3 and 3-4 years of implant experience is shown in Figure 4.23. It could be noted that the percentage of participants with correct phoneme production increased with longer implant use.

Table 4.47

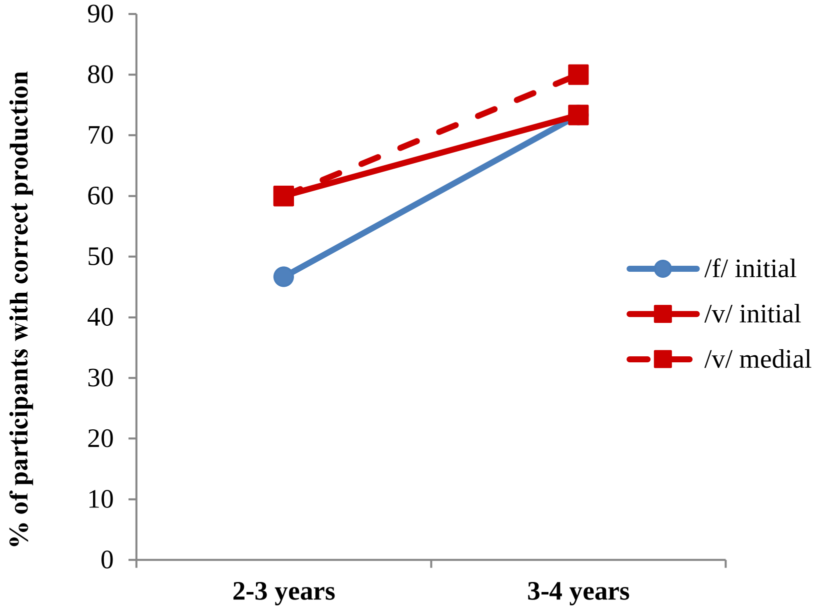
Percentage of Participants Exhibiting SODA Errors for Labiodentals across Phoneme Position in Children with 2-3 and 3-4 years of CI Experience

Phoneme	Initial				Medial			
	2-3 years		3-4 years		2-3 years		3-4 years	
	CR (%)	Err (%)	CR (%)	Err (%)	CR (%)	Err (%)	CR (%)	Err (%)
/f/	46.66	53.33 (S)	73.33	26.66 (S)	NT		NT	
/v/	60	40 (S)	73.33	20 (S) 6.66 (D)	60	40 (S)	80	20 (S)

Note. CR: correct responses, Err: error, S-substitution O- Omission D- Distortion A-Addition, NT-not tested

Figure 4.23

Percentage of Participants with Correct Production of Labiodentals with 2-3 and 3-4 Years of CI Experience



Substitution Error Analysis: Substitution errors with respect to place of articulation were analyzed for labiodentals and are tabulated in Table 4.48. Bilabial stops /p/ and /b/ were the most common phonemes substituted for labiodentals by the participants irrespective of implant experience and phoneme position. Percentage of participants with correct production and substitution errors of labiodentals in both groups of children using CI are as shown in Figure 4.24. Percentage of participants with correct production increased from 56.81% to 69.38% with increase in CI experience. The most common substitutions were with bilabials and palatals in participants with lesser implant experience whereas an increase in percentage of substitutions with bilabials was noted in participants with longer implant experience. Labiodentals were never substituted with another labiodental in both younger and older group of participants.

Table 4.48

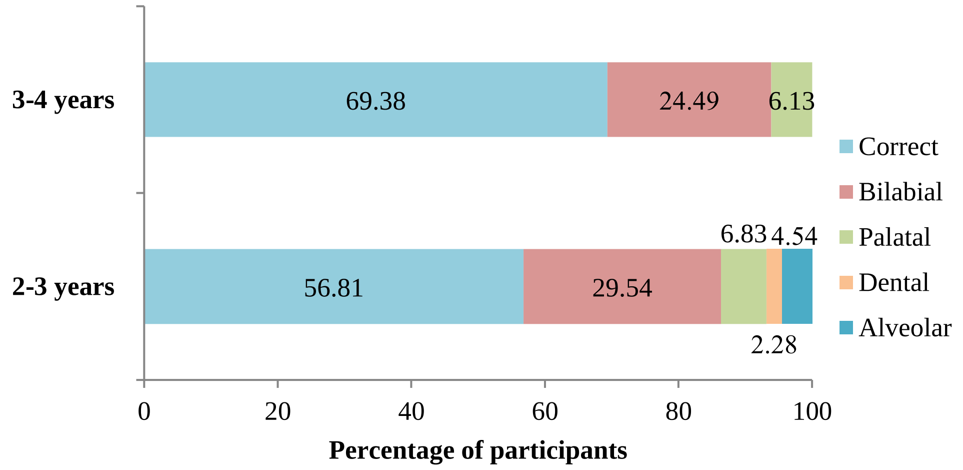
Substitution Errors of Labiodentals in Children with 2-3 and 3-4 years of CI Experience

Phoneme	Position	2-3 years				3-4 years			
		NPS	PS	POA	PPS (%)	NPS	PS	POA	PPS (%)
/f/	I	7	/p/ /c/ /s/	Bilabial Palatal Alveolar	57.14 14.28 28.57	9	/p/ /c/,/ʃ/	Bilabial Palatal	66.66 33.33
/v/	I	5	/b/	Bilabial	100	3	/b/,/p/	Bilabial	100
	M	6	/b/ /j/ /d/	Bilabial Palatal Dental	50 33.33 16.66	3	/b/	Bilabial	100

Note. NPS-Number of participants with substitution error, PPS (%)- Percentage of participants with substitution error, PS- phonemes substituted with, POA- place of articulation, I- initial, M- medial, F-final

Figure 4.24

Percentage of Participants with Correct Production and Substitution Errors of Labiodentals in Children with 2-3 and 3-4 years of CI Experience



3. Dentals.

The phonemes tested under dentals were /t/, /d/, their aspirated cognates /t^h/, /d^h/ and nasal /n̪/. The aspirated phonemes /t^h/ and /d^h/ were tested only in medial position and for older group of participants.

SODA Analysis: Results of SODA analysis of dental phonemes in both sub groups of CI are shown in Table 4.49. Dental stops were better produced initial position compared to medial position whereas, for nasal /n̪/ it was in medial position. Substitutions were the predominant type of error in dentals irrespective of phoneme position. /d/ was the most difficult phoneme among dentals in initial as well as medial positions in both groups of participants. Similar to bilabials, aspirated stops had the least accuracy compared to their unaspirated cognates for dentals also. Improvement in phoneme production was observed with increase in duration of implant use and is depicted in Figure 4.25.

Table 4.49

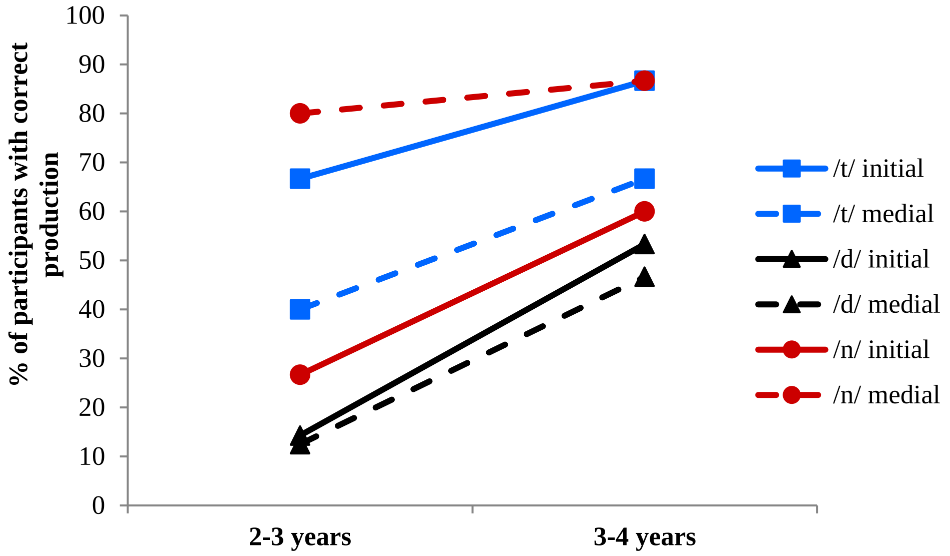
Percentage of Participants Exhibiting SODA Errors for Dentals across Phoneme Position in Children with 2-3 and 3-4 years of CI Experience

Phoneme	Initial				Medial			
	2-3 years		3-4 years		2-3 years		3-4 years	
	CR (%)	Err (%)	CR (%)	Err (%)	CR (%)	Err (%)	CR (%)	Err (%)
/t/	66.66	33.33 (S)	86.66	6.66 (S) 6.66 (O)	40	53.33 (S) 6.66 (A)	66.66	26.66 (S) 6.66 (A)
/t^h/	NT		NT		NT		40	60 (S)
/d/	14.28	71.43 (S) 14.28 (O)	53.33	26.66 (S) 20 (O)	12.5	37.5 (S) 25 (O) 25 (D)	46.66	40 (S) 13.33 (O)
/d^h/	NT		NT		NT		40	60(S)
/n̪/	26.66	66.66 (S) 6.66 (O)	60	33.33 (S) 6.66 (O)	80	20 (S)	86.66	6.66 (S) 6.66 (D)

Note. CR: correct responses, Err: error, S-substitution O- Omission D- Distortion A-Addition, NT-not tested

Figure 4.25

Percentage of Participants with Correct Production of Dentals with 2-3 and 3-4 years of CI Experience



Substitution Error Analysis: Substitution errors of dentals were analyzed with respect to the place of articulation and are summarized in Table 4.50. It could be observed that compared to bilabials and labiodentals, dentals were substituted with multiple class of phonemes including bilabials, alveolars, retroflexes, palatals and velars. Percentage of participants with correct production and substitution errors of dentals in both groups of participants are depicted in Figure 4.26. Percentage of participants with correct production increased from 49.28% to 61.53% with increase in duration of CI use. The percentage of substitution with dentals increased (7.24% to 10.25%). However, the percentage of substitution with other places of articulation remained similar with increase in implant experience.

Table 4.50

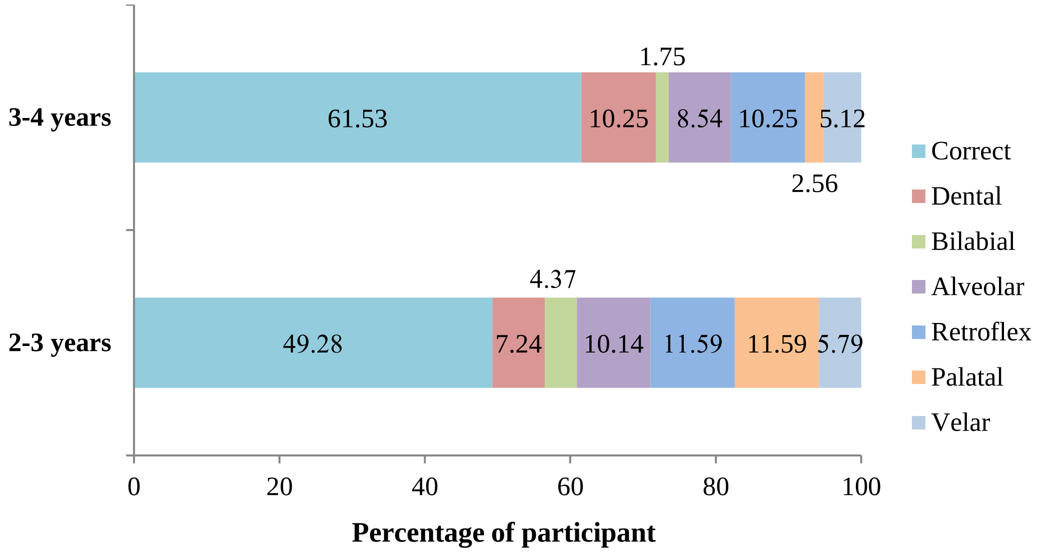
Substitution Errors of Dentals in Children with 2-3 and 3-4 years of CI Experience

Phoneme	Position	2-3 years				3-4 years			
		NPS	PS	POA	PPS (%)	NPS	PS	POA	PPS (%)
/t/	I	6	/ʈ/	Retroflex	50	1	/ʈ/	retroflex	100
			/k/	Velar	33.33				
			/r̠/	Alveolar	16.66				
	M	8	/j/	Palatal	50	4	/ɖ/,/ɳ/	Retroflex	100
			/ʈ/,/ɖ/	Retroflex	37.5				
			/l/	Alveolar	12.5				
/tʰ/	M	NT				9	/k/	Velar	66.66
							/l/	Alveolar	33.33
/d/	I	5	/k/	Velar	40	4	/ʈ/,/ɖ/	Retroflex	75
			/t/	Dental	40		/j/	Palatal	25
			/j/,/c/	Palatal	20				
	M	3	/j/	Palatal	66.66	6	/ʈ/,/ɖ/	Retroflex	50
			/t/	Dental	33.33		/m/	Bilabial	33.33
							/j/	Palatal	16.66
/dʰ/	M	NT				15	/d/,/t/	Dental	80
							/l/	Alveolar	20
/n̪/	I	10	/n/	Alveolar	40	5	/n/	Alveolar	80
			/p/,/m/	Bilabial	30		/c/	Palatal	20
			/d/	Dental	20				
			/c/	Palatal	10				
	M	3	/ɳ/	Retroflex	66.66	1	/ɳ/	Retroflex	100
			/n/	Alveolar	33.33				

Note. NPS-Number of participants with substitution error, PPS (%) - Percentage of participants with substitution error, PS- phonemes substituted with, POA- place of articulation, I- initial, M- medial, F-final, NT-not tested

Figure 4.26

Percentage of Participants with Correct Production and Substitution Errors of Dentals in Children with 2-3 and 3-4 years of CI Experience



4. Alveolars.

The phonemes tested under alveolars were /ṟ/ (unvoiced stop), /n/ (nasal), /l/ (lateral), /r/ (flap), /ṛ/ (trill) and /s/ (unvoiced fricative). All phonemes were tested in both initial and medial positions except unvoiced stop /ṟ/ and nasal /n/ which were tested in medial position only. Nasal /n/, lateral /l/ and trill /ṛ/ were tested in final position also.

SODA Analysis: Results of SODA analysis of alveolars in both sub groups of CI are shown in Table 4.51. Among the phonemes, /l/ showed the highest increase in correct production in initial and final positions irrespective of CI experience. Minimal improvement in correct production was observed for fricative /s/ in initial and medial positions and trill /ṛ/ in medial position. /ṛ/ and /r/ were the most difficult phonemes among alveolars irrespective of phoneme position and implant experience of the participants. The improvement in accuracy of production with increase in implant experience in initial is shown in Figure 4.27, medial position in Figure 4.28 and final positions in Figure 4.29. Except /s/ in medial position, all phonemes exhibited varying degrees of improvement with implant experience.

Figure 4.27

Percentage of Participants with Correct Production of Alveolars in Word-Initial Position with 2-3 and 3-4 years of CI Experience

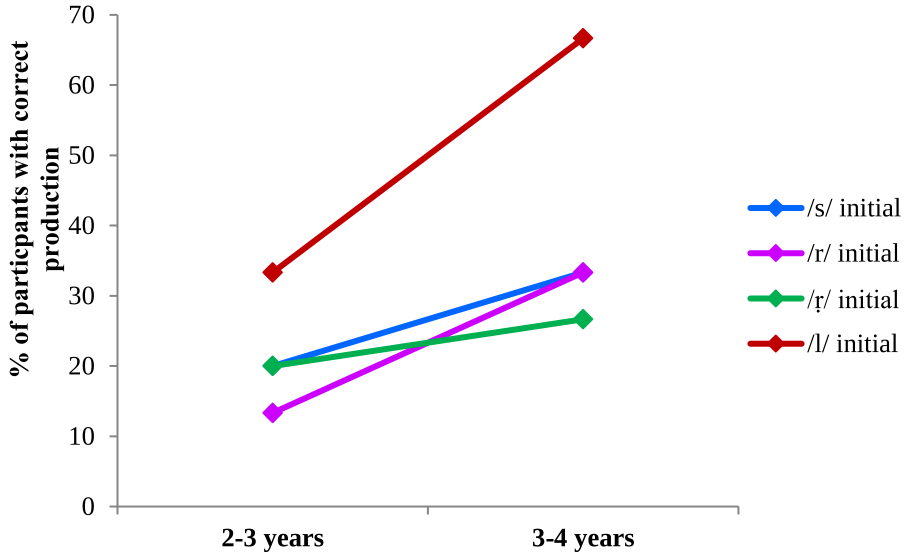


Figure 4.28

Percentage of Participants with Correct Production of Alveolars in Word-Medial Position with 2-3 and 3-4 years of CI Experience

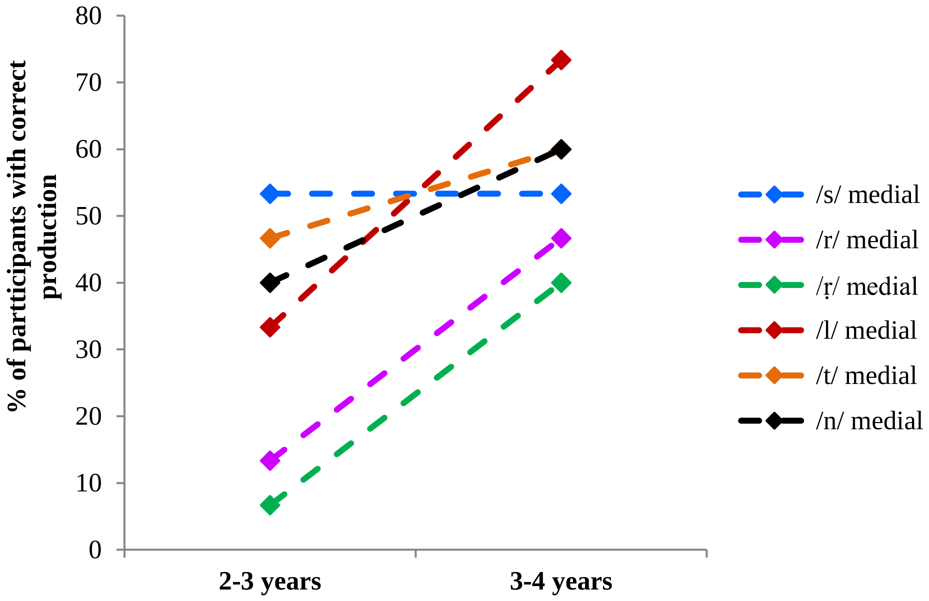


Table 4.51

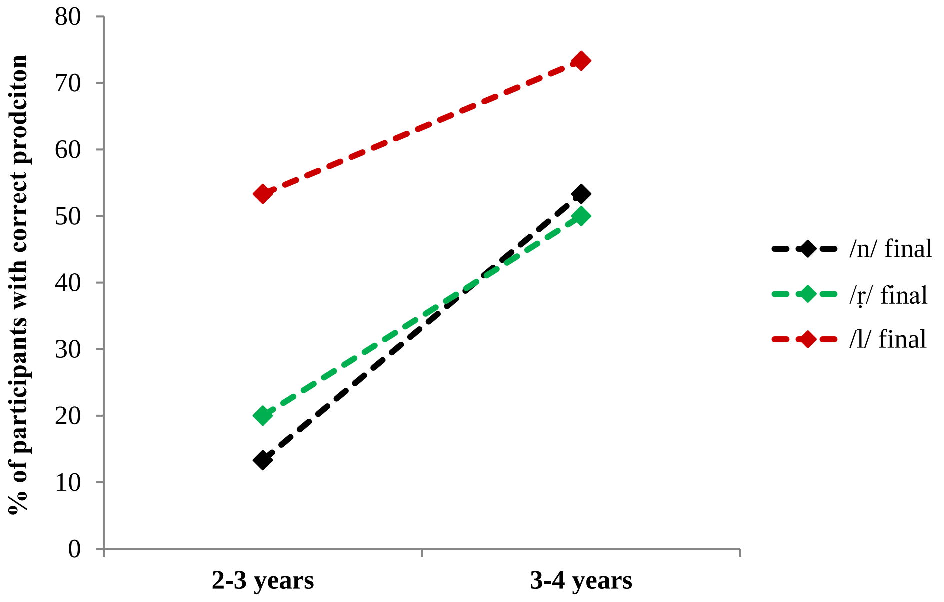
Percentage of Participants Exhibiting SODA Errors for Alveolars across Phoneme Position in Children with 2-3 and 3-4 years of CI Experience

Phoneme	Initial				Medial				Final			
	2-3 years		3-4 years		2-3 years		3-4 years		2-3 years		3-4 years	
	CR (%)	Err (%)	CR (%)	Err (%)	CR (%)	Err (%)	CR (%)	Err (%)	CR (%)	Err (%)	CR (%)	Err (%)
/n/	NT		NT		40	60 (S)	60	40(S)	13.33	40 (S) 46.66 (O)	46.66	26.66 (S) 26.66 (O)
/s/	20	80 (S)	33.33	66.66 (S)	53.33	46.66 (S)	53.33	46.66 (S)	NT		NT	
/ṟ/	NT		NT		46.66	53.33 (S)	60	40 (S)	NT		NT	
/r/	20	80 (S)	33.33	53.33 (S) 13.33 (D)	13.33	33.33 (S) 33.33 (O) 20 (D)	46.66	33.33 (S) 20 (O)	NT		NT	
/ṛ/	20	80 (S)	26.66	46.66 (S) 20 (O) 6.66 (D)	6.66	26.66 (S) 60 (O) 6.66 (D)	40	53.33 (S) 6.66 (O)	20	20(S) 40 (O) 20 (D)	33.33	40 (S) 13.33 (O) 13.33 (D)
/l/	33.33	60 (S)	66.66	33.33 (S)	33.33	53.33 (S) 6.66 (O)	73.33	20(S) 6.66 (O)	53.33	26.66 (S) 20 (O)	73.33	13.33 (S) 13.33 (O)

Note. CR-correct responses, Err: error, S-substitution O- Omission D- Distortion A-Addition, NT-not tested

Figure 4.29

Percentage of Participants with Correct Production of Alveolars in Word-Final Position with 2-3 and 3-4 years of CI Experience



Substitution Error Analysis: The substitution errors of alveolars were analyzed with respect to place of articulation and is as shown in Table 4.52. Alveolars were substituted with a variety of places of articulation except glottals, especially in younger group of participants. Percentage of participants with correct production and substitution errors of alveolars in both groups of participants are shown in Figure 4.30. As the duration if CI use increased, percentage of participants with correct production increased from 38.35% to 56.06%. With increase in implant experience, substitutions with same POA (alveolars) increased (4.10% to 14.45%) and those with palatals decreased (36.98% to 15.6%).

Table 4.52

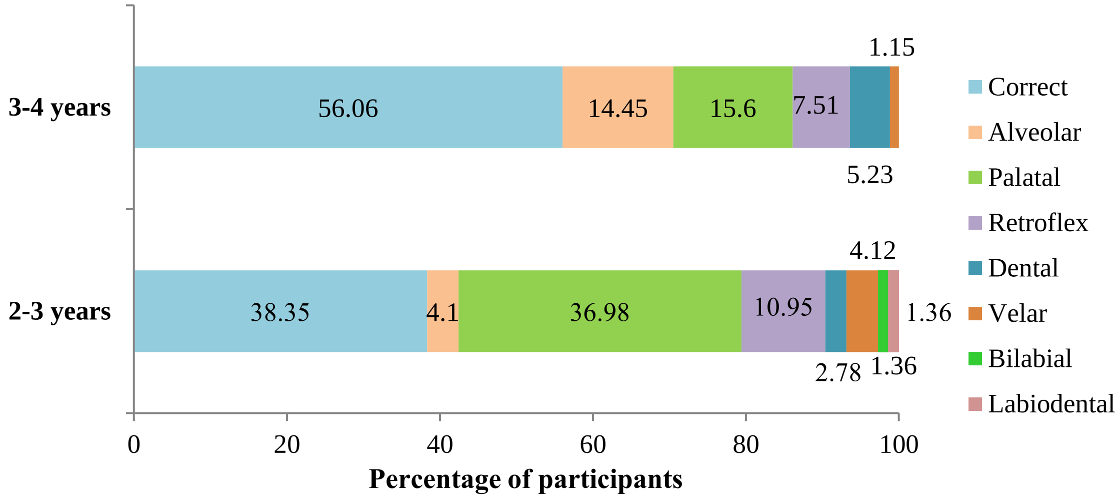
Substitution Errors of Alveolars in Children with 2-3 and 3-4 years of CI Experience

Phoneme	Position	2-3 years				3-4 years			
		NPS	PS	POA	PPS (%)	NPS	PS	POA	PPS (%)
/n/	M	8	/j/,/ɲ/	Palatal	75	6	/l/	Alveolar	50
			/g/	Velar	25		/j/,/ɲ/	Palatal	50
	F	6	/l/	Alveolar	16.66	4	/l/	Alveolar	50
			/m/	Bilabial	33.33		/j/	Palatal	25
			/j/	Palatal	50		/ɳ/	Retroflex	25
/s/	I	11	/c/,/j/ /ʃ/	Palatal	100	10	/c/,/j/ /ʃ/	Palatal	100
	M	6	/c/, /ʃ/	Palatal	33.33	6	/c/,/ʃ/	Palatal	83.33
			/ʂ/	Retroflex	16.66		/t/	Dental	16.66
			/k/	Velar	50				
/r̠/	M	8	/c/	Palatal	62.5	6	/c/	Palatal	33.33
			/t/	Dental	25		/t/	Dental	50
			/ʈ/	Retroflex	12.5		/ʈ/	Retroflex	16.66
/r/	I	11	/c/,/j/	Palatal	72.72	8	/s/,/l/	Alveolar	25
			/t/	Dental	9.09		/ʈ/,/ɖ/	Retroflex	37.5
			/v/	Labiodental	9.09		/c/,/j/	Palatal	37.5
			/g/	Velar	9.09				
	M	4	/l/	Alveolar	25	5	/d/	Dental	60
			/ɖ/	Retroflex	25		/ɖ/	Retroflex	20
			/j/	Palatal	50		/j/	Palatal	20
/ṛ/	I	11	/s/	Alveolar	9.09	7	/r/	Alveolar	42.85
			/j/	Palatal	81.81		/j/	Palatal	14.28
			/ʈ/	Retroflex	9.09		/g/	Velar	28.57
							/t/	Dental	14.28
	M	4	/ɖ/, /ɭ/	Retroflex	100	8	/ɖ/,/ɭ/	Retroflex	75
							/r/	Alveolar	25
	F	3	/ɭ/	Retroflex	66.66	6	/l/	Alveolar	83.33
			/v/	Labiodental	33.33		/ɭ/	Retroflex	16.66
/l/	I	7	/j/	Palatal	57.14	4	/r/,/ṛ/	Alveolar	75
			/ɭ/	Retroflex	28.57		/d/	Dental	25
			/d/	Dental	14.28				
	M	7	/ɭ/,/ɖ/	Retroflex	57.14	3	/n/,/r/	Alveolar	66.66
			/j/	Palatal	28.57		/j/	Palatal	33.33
			/n/	Alveolar	14.28				
	F	4	/j/	Palatal	50	2	/n/	Alveolar	100
			/r/,/n/	Alveolar	50				

Note. NPS-Number of participants with substitution error, PPS(%)- Percentage of participants with substitution error, PS- phonemes substituted with, POA- place of articulation, I- initial, M- medial, F-final

Figure 4.30

Percentage of Participants with Correct Production and Substitution Errors of Alveolars in Children with 2-3 and 3-4 years of CI Experience



5. Retroflex.

The phonemes tested under retroflex were unvoiced stop /ʈ/, its aspirated cognate /ʈ^{h}/, voiced stop /ɖ/, nasal /ɳ/, fricative /ʂ/, lateral /ɭ/ and approximant /ʐ/. Among the seven phonemes, /ʈ/, /ɖ/ and /ʂ/ were tested in both initial and medial positions and /ʈ^{h}/, /ɳ/, /ʐ/ and /ɭ/ were tested in medial position. /ɳ/ and /ɭ/ were tested in final position.

SODA analysis: Results of SODA analysis of retroflex phonemes in both sub groups of CI are shown in Table 4.53. In word initial position, unvoiced stop /ʈ/ was the most correctly produced phoneme by majority of the participants in both younger and older groups. Voiced stop /ɖ/ and fricative /ʂ/ were the most difficult phonemes in the initial position. In medial position, lateral /ɭ/ was produced with greatest accuracy by most of the participants of both the groups of CI, whereas /ʂ/ and /ɳ/ were the most difficult phonemes in the medial position. It was also interesting to note that retroflex approximant /ʐ/ was never produced correctly by any of the participants in both groups. Improvement in phoneme production was observed with increase in duration of implant use and is depicted in Figure 4.31 and Figure 4.32.

Figure 4.31

Percentage of Participants with Correct Production of Retroflexes in Word-Initial Position with 2-3 and 3-4 years of CI Experience

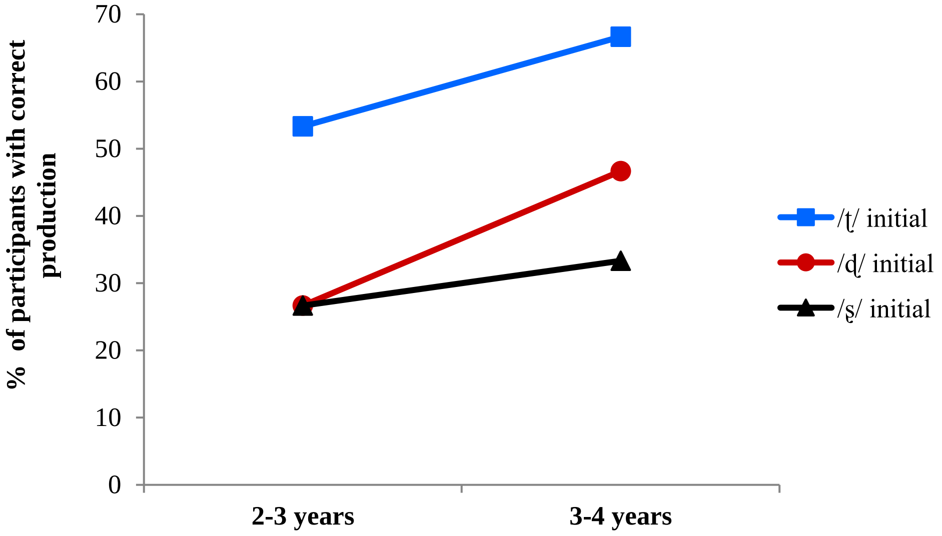


Figure 4.32

Percentage of Participants with Correct Production of Retroflex Phonemes in Word-Medial and Word-Final Positions with 2-3 and 3-4 years of CI Experience

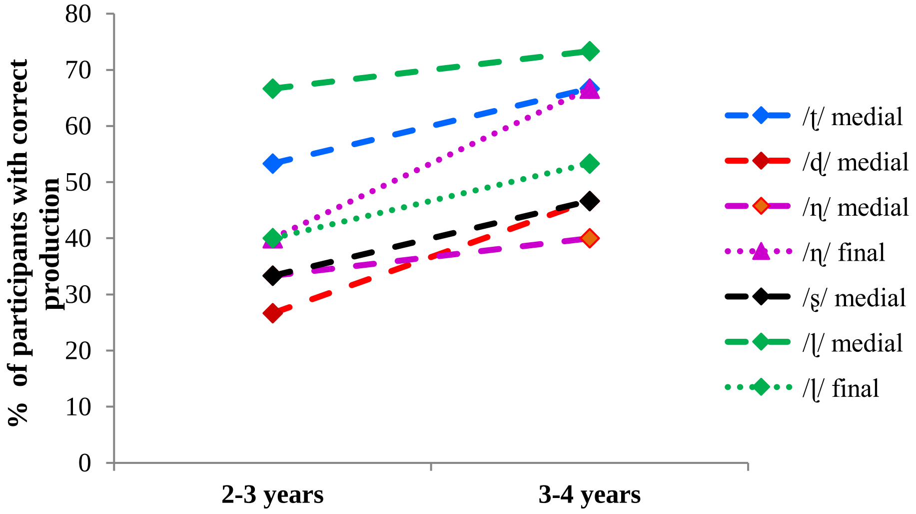


Table 4.53

Percentage of Participants Exhibiting SODA Errors for Retroflexes across Phoneme Position in Children with 2-3 and 3-4 years of CI Experience

Phoneme	Initial				Medial				Final			
	2-3 years		3-4 years		2-3 years		3-4 years		2-3 years		3-4 years	
	CR (%)	Err (%)	CR (%)	Err (%)	CR (%)	Err (%)	CR (%)	Err (%)	CR (%)	Err (%)	CR (%)	Err (%)
/ʈ/	53.33	46.66 (S)	66.66	26.66(S) 6.66 (D)	53.33	46.66 (S)	66.66	26.66 (S) 6.66 (O)	NT		NT	
/ʈʰ/	NT		NT		NT		60	40 (S)	NT		NT	
/ɖ/	26.66	73.33 (S)	46.66	40 (S) 13.33 (D)	26.66	66.66(S) 6.66 (O)	46.66	53.33(S)	NT		NT	
/ɳ/	NT		NT		33.33	66.66 (S)	40	60(S)	40	40 (S) 20 (O)	66.66	26.66 (S) 6.66 (O)
/ʂ/	26.66	66.66 (S) 6.66 (O)	33.33	60 (S) 6.66 (D)	33.33	66.66 (S)	46.66	53.33 (S)	NT		NT	
/ɭ/	NT		NT		66.66	33.33(S)	73.33	26.66 (S)	40	53.33 (S) 6.66 (O)	53.33	40 (S) 6.66 (O)
/ʐ/	NT		NT		0	80(S) 20(O)	0	100(S)	NT		NT	

*Note.*CR: correct responses, Err: error, S-substitution O- Omission D- Distortion A-Addition, NT-not tested

Substitution Error Analysis: The substitution errors of retroflex phonemes were analyzed with respect to place of articulation and is shown in Table 4.54. Retroflex phonemes were substituted with multiple Places of articulation (six) in younger group of participants and this variability did not reduce considerably with increase in implant experience. Predominant substitutions were with dentals, alveolars and palatals in both groups of CI. Percentage of participants with correct production and substitution errors of retroflex in both groups of participants are shown in Figure 4.33. Overall percentage of participants with correct production increased from 40.28% to 50.27%. With increase in CI experience, a slight increase in percentage of substitutions with same place of articulation (retroflex) was noted (1.34%% to 5.58%). However compared to other POAs, this increase can be considered as minimal.

Table 4.54

Substitution Errors of Retroflex Phonemes in Children with 2-3 and 3-4 years of CI Experience

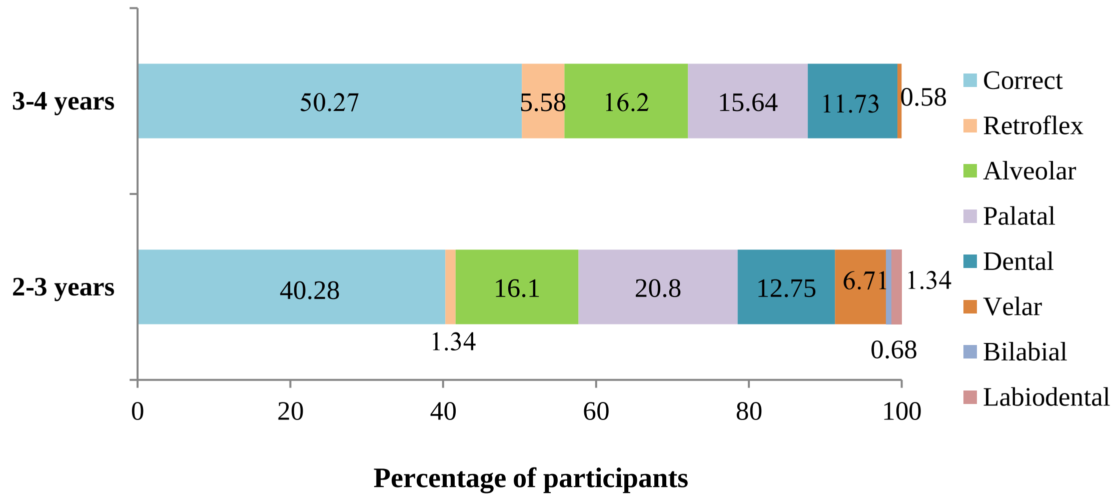
Phoneme	Position	2-3 years				3-4 years			
		NPS	PS	POA	PPS (%)	NPS	PS	POA	PPS (%)
/ʈ/	I	7	/ṟ/ /v/ /t/ /k/	Alveolar Labiodental Dental Velar	28.57 28.57 28.57 14.28	4	/t/	Dental	100
	M	7	/t/ /c/ /k/	Dental Palatal Velar	57.14 28.57 14.28	4	/t/ /ṟ/	Dental Alveolar	75 25
/ʈ^h/	M			NT		6	/ʈ/ /ṟ/	Retroflex Alveolar	50 50
/ɖ/	I	11	/ʈ/,/t/ /d/ /k/,/g/	Retroflex Dental Velar	9.09 36.36 54.54	6	/ʈ/ /d/ /j/	Retroflex Dental Palatal	16.66 66.66 16.66
	M	10	/ʈ/ /t/,/d/ /r/ /j/ /g/	Retroflex Dental Alveolar Palatal Velar	10 50 10 20 10	8	/ʈ/ /d/ /ṛ/	Retroflex Dental Alveolar	37.50 50 12.50

Phoneme	Position	2-3 years				3-4 years			
		NPS	PS	POA	PPS (%)	NPS	PS	POA	PPS (%)
/ɳ/	M	7	/j/,/ɲ/	Palatal	57.14	10	/j/	Palatal	20
			/n/	Dental	14.28		/l/,/n/	Alveolar	70
			/r/	Alveolar	14.28		/r/		
			/g/	Velar	14.28		/ŋ/	Velar	10
	F	3	/n/	Alveolar	66.67	5	/n/	Alveolar	60
			/m	Bilabial	33.33		/n/	Dental	40
/ʂ/	I	9	/ʃ/,/c/	Palatal	55.55	9	/ʈ/	Retroflex	11.11
			/s/,/r̠/	Alveolar	22.22		/ʃ/,/c/	Palatal	77.77
			/t/	Dental	22.22		/t/	Dental	11.11
	M	10	/ʃ/,/c/	Palatal	60	8	/ʃ/,/c/	Palatal	62.50
			/s/	Alveolar	40		/s/	Alveolar	37.50
/ɭ/	M	5	/j/	Palatal	60	4	/l/	Alveolar	100
			/n/	Dental	20				
			/l/	Alveolar	20				
	F	8	/l/	Alveolar	87.5	7	/ɳ/	Retroflex	28.57
			/j/	Palatal	12.5		/l/	Alveolar	57.14
							/j/	Palatal	14.28
/ʐ/	M	15	/j/	Palatal	73.33	15	/j/	Palatal	80
			/l/	Alveolar	26.66		/l/	Alveolar	20

Note. NPS-Number of participants with substitution error, PPS(%)- Percentage of participants with substitution error, PS- phonemes substituted with, POA- place of articulation, I- initial, M- medial, F-final, NT- Not tested

Figure 4.33

Percentage of Participants with Correct Production and Substitution Errors of Retroflexes in Children with 2-3 and 3-4 years of CI Experience



6. Palatals

Palatal phonemes tested include unvoiced affricate /c/, voiced affricate /ɟ/, nasal /ɲ/, glide /j/ and fricative /ʃ/. All the five phonemes were tested in both initial and medial positions.

SODA analysis: Results of SODA analysis of palatals in both sub groups of CI are shown in Table 4.55. In initial position, affricate /c/ and glide /j/ were the best articulated phonemes in both groups of CI. Nasal /ɲ/ was the most difficult phoneme in the initial position for younger group of participants, i.e. none of the 15 participants were able to produce the phoneme correctly. In medial position, /c/ and /j/ were correctly produced by majority of the participants in older group and /c/ and /ʃ/ in younger group of participants. Voiced affricate /ɟ/ was the most difficult phoneme in the medial position irrespective of implant experience of the participants. Improvement in accuracy of phoneme production was observed with increase in duration of implant use in initial position is depicted in figure 4.34 and medial position in Figure 4.35.

Table 4.55

Percentage of Participants Exhibiting SODA Errors for Palatals across Phoneme Position in Children with 2-3 and 3-4 years of CI Experience

Phoneme	Initial				Medial			
	2-3 years		3-4 years		2-3 years		3-4 years	
	CR (%)	Err (%)	CR (%)	Err (%)	CR (%)	Err (%)	CR (%)	Err (%)
/c/	66.66	20(S) 13.33 (O)	73.33	20 (S) 6.66(O)	80	13.33 (S) 6.66(A)	93.33	6.66(D)
/c^h/	NT		60	40(S)	NT		NT	
/ɟ/	26.66	73.33(S)	60	40 (S)	20	80 (S)	33.33	60(S) 6.66(D)

Phoneme	Initial				Medial			
	2-3 years		3-4 years		2-3 years		3-4 years	
	CR (%)	Err (%)	CR (%)	Err (%)	CR (%)	Err (%)	CR (%)	Err (%)
/ɲ/	0	93.33(S) 6.66 (O)	53.33	40 (S) 6.66 (O)	73.33	20(S) 6.66 (O)	80	20 (S)
/ʃ/	40	60(S)	46.66	40 (S) 13.33 (O)	80	20 (S)	86.66	13.33 (S)
/j/	66.66	26.66(S) 6.66 (O)	80	13.33 (S) 6.66 (O)	73.33	13.33 (S) 13.33(O)	93.33	6.66 (S)

Note. CR: correct responses, Err: error, S-substitution O- Omission D- Distortion A-Addition, NT-not tested

Figure 4.34

Comparison of Percentage of Correct Production of Palatals in Children with 2-3 and 3-4 years of CI Experience

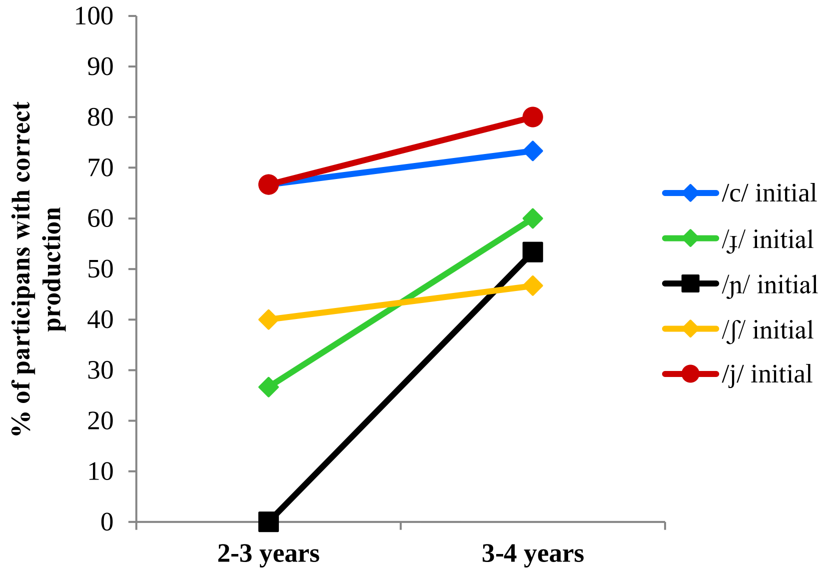
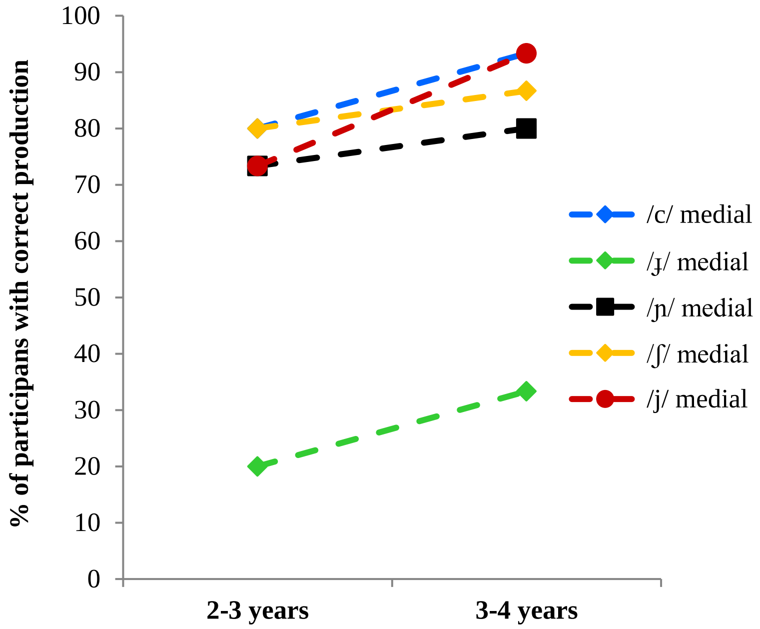


Figure 4.35

Comparison of Percentage of Correct Production of Palatals in Children with 2-3 and 3-4 years of CI Experience



Substitution Error Analysis: Substitution errors of palatals were analyzed with respect to place of articulation and is shown in Table 4.56. The overall number of substitutions reduced with increase in implant experience. Palatal-palatal substitutions were consistently observed in both groups. Percentage of participants with correct production and substitution errors of palatals in both groups of participants are shown in figure 4.36. With increase in duration of CI use, percentage of participants with correct productions of palatals increased from 58.41% to 71.72%. A notable reduction in percentage of substitutions with same place of articulation with increase in implant experience was observed (30.14% to 16.35%). This is due to an overall reduction in the number of substitution errors in older group. The overall variability in places of articulation used for substitutions remained similar with increase in implant experience.

Table 4.56

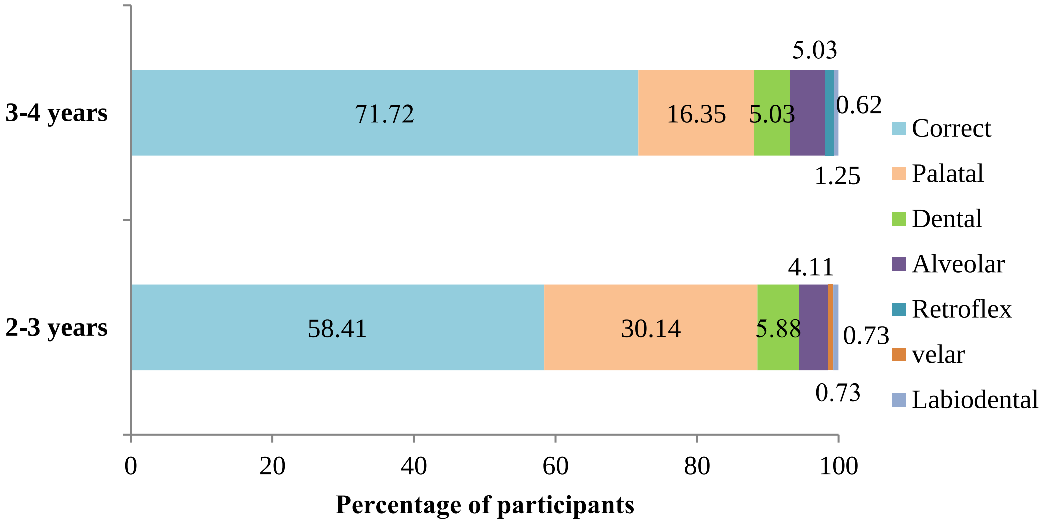
Substitution Errors of Palatals in Children with 2-3 and 3-4 years of CI Experience

Phoneme	Position	2-3 years				3-4 years			
		NPS	PS	POA	PPS (%)	NPS	PS	POA	PPS (%)
/c/	I	2	/t/	Dental	50	3	/ɟ/	Palatal	100
			/ʃ/	Palatal	50		/ʃ/		
	M	2	/ʃ/	Palatal	100	-	-	-	-
/cʰ/	I	NT				6	c	Palatal	100
/ɟ/	I	9	/c/,/j/	Palatal	88.89	6	/c/,/cʰ/	Palatal	33.33
			/d/	Dental	11.11		/t/,/d/	Dental	50
							/ʈ/	Retroflex	16.66
	M	12	/c/,/j/	Palatal	66.66	10	/c/,/j/	Palatal	60
			/t/	Dental	8.33		/t/,/d/	Dental	30
			/v/	Labiodental	8.33		/r/	Alveolar	10
			/r/	Alveolar	16.66				
/ɲ/	I	14	/j/,/c/	Palatal	57.14	6	/j/	Palatal	50
			/t/,/d/	Dental	35.71		/n/,/r/	Alveolar	33.33
			/r/	Alveolar	7.14		/v/	Labiodental	16.67
	M	3	/n/	Alveolar	66.67	3	/n/	Alveolar	66.67
			/ŋ/	Velar	33.33		/ɳ/	Retroflex	33.33
/ʃ/	I	7	/c/	Palatal	100	6	/c/	Palatal	66.67
							/s/	Alveolar	33.33
	M	2	/c/,/ɲ/	Palatal	100	2	/c/	Palatal	100
/j/	I	4	/c/,/ɲ/	Palatal	100	2	/t/	Dental	100
	M	2	/ʃ/	Palatal	50	1	/l/	Alveolar	100
			/l/	Alveolar	50				

Note. NPS-Number of participants with substitution error, PPS (%)- Percentage of participants with substitution error, PS- phonemes substituted with, POA- place of articulation, I- initial, M- medial, F-final, NT-Not tested

Figure 4.36

Percentage of Participants with Correct Production and Substitution Errors of Palatals in Children with 2-3 and 3-4 years of CI Experience



7. Velars and Glottal

Phonemes tested include unvoiced stop /k/, voiced stop /g/, their aspirated cognates /k^h/, /g^h/, nasal / ŋ/ and fricative /h/. /k/ and /g/ were tested in the word initial position in both younger and older groups of participants. All phonemes were tested in the medial position for both the group of participants. Aspirated stops were tested only for older group of participants.

SODA Analysis: Results of SODA analysis of velars and glottals in both sub groups of CI are shown in Table 4.57. An increase in the percentage of correct phoneme production was observed with increase in duration of implant use is depicted in Figure 4.37. Unvoiced stop /k/ was the most correctly produced phoneme by majority of the participants irrespective of phoneme position and duration of CI use. Voiced stop /g/ was the most difficult phoneme in the word initial and medial positions for younger group of participants. Aspirated stops had the least accuracy of production for older group of participants. Glottal /h/ had only omission errors and therefore not discussed under substitution pattern analysis.

Table 4.57

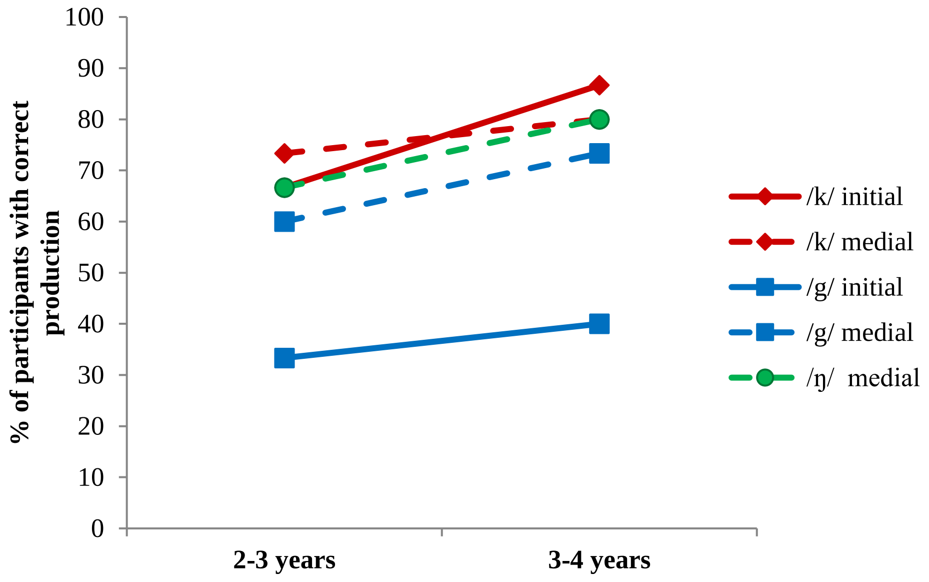
Percentage of Participants Exhibiting SODA Errors for Velars across Phoneme Position in Children with 2-3 and 3-4 years of CI Experience

Phoneme	Initial				Medial			
	2-3 years		3-4 years		2-3 years		3-4 years	
	CR (%)	Err (%)	CR (%)	Err (%)	CR (%)	Err (%)	CR (%)	Err (%)
/k/	66.66	13.33(S) 20 (O)	86.66	13.33 (O)	73.33	20 (S) 6.66 (O)	80	20 (S)
/kʰ/	NT		20	80 (S)	NT		20	80 (S)
/g/	33.33	66.66(S)	40	53.33 (S) 6.66 (O)	60	40 (S)	73.33	26.66 (S)
/gʰ/	NT		NT		NT		20	80 (S)
/ŋ/	NT		NT		66.66	33.33 (S)	80	20 (S)
/h/	NT		NT		NT		60	40 (O)

Note. CR: correct responses, Err: error, S-substitution O- Omission D- Distortion A-Addition, NT-not tested

Figure 4.37

Percentage of Participants with Correct Production of Velars with 2-3 and 3-4 Years of CI Experience



Substitution Error Analysis: The substitution errors of velars were analyzed with respect to place of articulation and are as shown in Table 4.58. Percentage of participants with correct production and substitution errors of velars in both groups of participants are shown in Figure 4.38. Percentage of correct productions increased from 66.17% to 75%. With increase in duration of CI use, the percentage of substitutions with dentals decreased (19.11% to 12.50%).

Table 4.58

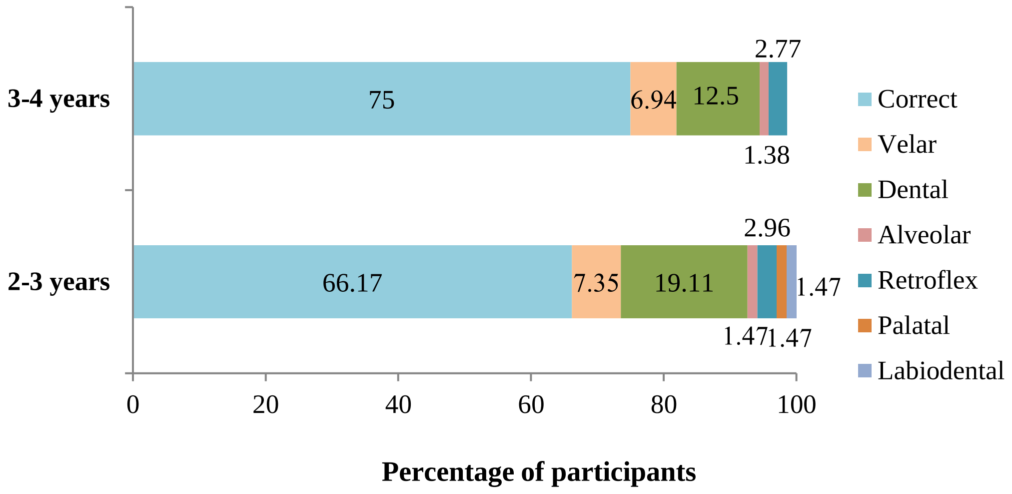
Substitution Errors of Velars in Children with 2-3 and 3-4 years of CI Experience

Phoneme	Position	2-3 years				3-4 years			
		NPS	PS	POA	PPS (%)	NPS	PS	POA	PPS (%)
/k/	I	2	/g/	Velar	50	0			
			/t/	Dental	50				
	M	3	/t/	Dental	100	3	/t/	Dental	100
/kʰ/	I	NT				11	/k/,/g/	Velar	45.45
							/t/	Dental	27.27
							/h/	Glottal	27.27
	M	NT				12	/k/	velar	100
/g/	I	9	/k/	Velar	22.22	8	/k/	Velar	25
			/t/,/d/	Dental	33.33		/t/,/d/	Dental	62.5
			/ɖ/	Retroflex	22.22		/n̪/		
			/j/	Palatal	11.11		/ɳ/	Retroflex	12.5
			/v/	Labiodental	11.11				
	M	4	/k/	Velar	50	4	/k/	Velar	75
			/t/,/d/	Dental	50		/t/	Dental	25
/gʰ/	M	NT				12	/k/	Velar	25
							/h/	Glottal	75
/ŋ/	M	5	/n̪/	Dental	80	3	/ɳ/	Retroflex	66.66
			/n/	Alveolar	20		/n/	Alveolar	33.33

Note. NPS-Number of participants with substitution error, PPS (%)- Percentage of participants with substitution error, PS- phonemes substituted with, POA- place of articulation, I- initial, M- medial, F-final, NT-Not tested

Figure 4.38

Percentage of Participants with Correct Production and Substitution Errors of Velars in Children with 2-3 and 3-4 years of CI Experience



4.2.2.2.2. Errors of Manner of Articulation.

The consonants were grouped according to manner of articulation and the results of SODA and PMV analyses were tabulated. The manners of articulation considered include stops, nasals, fricatives, affricates, and approximants (trill, flap, glides, laterals and approximant /ɻ/) and the results will be discussed under those sections. Percentage of participants exhibiting SODA errors was tabulated under respective manners of articulation. Substitution pattern analysis with respect to manner of articulation will be discussed in this section.

1. Stops.

Fifteen stops including 9 unaspirated and 6 aspirated were analyzed. Stops at various places of articulation were tested which includes bilabials (/p/, /b/, /b^h/), dentals (/t/, /t^h/, /d/, /d^h/), alveolar (r̠), retroflex (/ʈ/, /ʈ^h/, /ɖ/) and velars (/k/, /k^h/, /g/, /g^h/). All unaspirated stops were tested in both initial and medial positions except the unvoiced alveolar stop /r̠/ which was tested in medial position only. Among the aspirated stops, /bʰ/ and /kʰ/ were tested in initial position and /tʰ/, /dʰ/, /ʈʰ/, /kʰ/ and /gʰ/ were tested in medial position. Also the aspirated stops were tested for older group of participants only.

SODA Analysis: Percentage of correct production, substitution, omission, distortion and addition errors of stops in both subgroups of children using CI are as shown in Table 4.59. As the duration of implant use increased, higher percentage of participants produced stops correctly. The improvement in accuracy of production in initial and medial positions with increase in implant experience is represented in Figure 4.39 and Figure 4.40. Among stops, /p/ was the most correctly produced phoneme by majority of the participants and exhibited the highest accuracy in percentage irrespective of the phoneme position and implant experience of the participants. In general unvoiced stops were produced correctly by higher percentage of participants compared to their voiced cognates. In younger group of participants, /d/ was the most difficult stop, whereas in older group of participants, velar aspirated stops /kʰ/ and /gʰ/ were the most difficult. Substitutions were the most predominant type of error exhibited by the participants irrespective of the implant experience. Overall aspirated stops were difficult compared to their unaspirated cognates.

Table 4.59

Percentage of Participants Exhibiting SODA Errors of Stops across Phoneme Position in Children with 2-3 and 3-4 years of CI Experience

Phoneme	Initial				Medial			
	2-3 years		3-4 years		2-3 years		3-4 years	
	CR (%)	Err (%)	CR (%)	Err (%)	CR (%)	Err (%)	CR (%)	Err (%)
/p/	66.66	33.33 (O)	100	0	80	20 (S)	93.33	6.66 (S)
/b/	26.66	66.66 (S) 6.66 (D)	60	40 (S)	60	40 (S)	80	20 (S)

Phoneme	Initial				Medial			
	2-3 years		3-4 years		2-3 years		3-4 years	
	CR (%)	Err (%)	CR (%)	Err (%)	CR (%)	Err (%)	CR (%)	Err (%)
/bʰ/	NT		20	80 (S)	NT		NT	
/t/	66.66	33.33 (S)	86.66	6.66 (S) 6.66 (O)	40	53.33 (S) 6.66 (A)	66.66	26.66 (S) 6.66 (A)
/tʰ/	NT		NT		NT		40	60 (S)
/d/	14.28	71.43 (S) 14.28 (O)	53.33	26.66 (S) 20 (O)	12.5	37.5 (S) 25 (O) 25 (D)	46.66	40 (S) 13.33 (O)
/dʰ/	NT		NT		NT		40	60(S)
/r̠/	NT		NT		46.66	53.33 (S)	60	40 (S)
/ʈ/	53.33	46.66 (S)	66.66	26.66(S) 6.66 (O)	53.33	46.66 (S)	66.66	26.66 (S) 6.66 (O)
/ʈʰ/	NT		NT		NT		60	40 (S)
/ɖ/	26.66	73.33 (S)	46.66	40 (S) 13.33 (D)	26.66	66.66(S) 6.66 (O)	46.66	53.33(S)
/k/	66.66	13.33(S) 20 (O)	86.66	13.33 (O)	73.33	20 (S) 6.66 (O)	80	20 (S)
/kʰ/	NT		20	80 (S)	NT		20	80 (S)
/g/	33.33	66.66(S)	40	53.33 (S) 6.66 (O)	60	40 (S)	73.33	26.66 (S)
/gʰ/	NT		NT		NT		20	80 (S)

Note. CR: correct responses, Err: error, S-substitution O- Omission D- Distortion A-Addition, NT-not tested

Figure 4.39

Percentage of Participants with Correct Production of Stops in Word-Initial Position in Children with 2-3 and 3-4 years of CI Experience

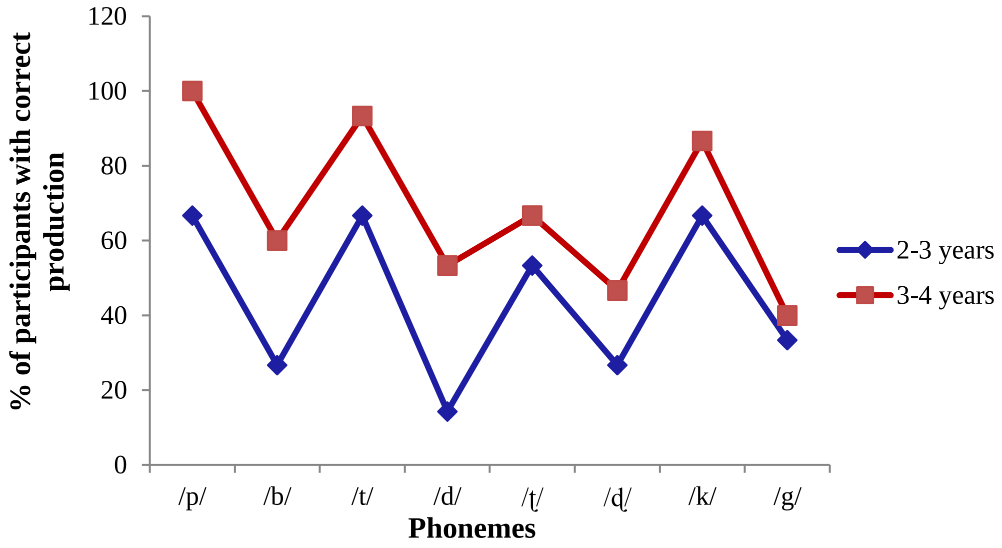
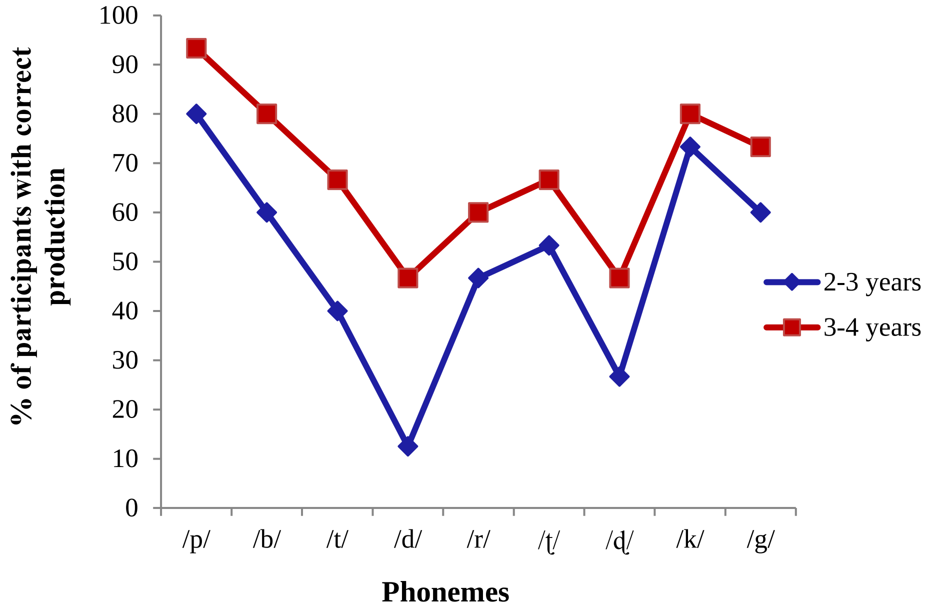


Figure 4.40

Percentage of Participants with Correct Production of Stops in Word-Medial Position in Children with 2-3 and 3-4 years of CI Experience



Substitution Error Analysis: Analysis of substitution errors of unvoiced and voiced stops with respect to manner of articulation in both groups of children using CI is as shown in Table 4.60 and Table 4.61 respectively. Unvoiced alveolar stop /ṟ/ was predominantly substituted with unvoiced palatal affricate /c/ (62.5%). Substitution of stops with nasals was observed only in older group of children for bilabial (/b/), dental (/t/) and velar (/g/) stops. Percentage of participants with correct production and substitution errors of stops in both groups of participants are shown in Figure 4.41. Percentage of participants with correct production with correct production increased from 54.09% to 58.49%. It could be evidenced that stops were predominantly substituted with other stops and glides.

Table 4.60

Substitution Errors of Unvoiced Stops in Children with 2-3 and 3-4 years of CI Experience

Phoneme	Position	2-3 years				3-4 years			
		NPS	PS	MOA	PPS (%)	NPS	PS	MOA	PPS (%)
/p/	I	0	-			0			
	M	3	/t/,/d/ /v/	Stop Glide	66.66 33.33	1	/t/	Stop	100
/t/	I	6	/ʈ/,/k/, /r̲/	Stop	100	1	/ʈ/	Stop	100
	M	8	/ʈ/,/ɖ/ /j/ /l/	Stop Glide Lateral	37.5 50 12.5	4	/ɖ/ /ɳ/	Stop Nasal	50 50
/tʰ/	M		NT			9	/k/ /l/	Stop Lateral	66.66 33.33
/r̲/	M	8	/c/ /t/,/ʈ/	Affricate Stop	62.5 37.5	6	/c/ /t/,/ʈ/	Affricate Stop	33.33 66.66
/ʈ/	I	7	/r̲/,/t/ /k/ /v/	Stop Glide	71.42 28.57	4	/t/	Stop	100
	M	7	/t/,/k/ /c/	Stop Affricate	85.71 14.28	4	/t/,/r̲/	Stop	100
/ʈʰ/	M		NT			6	/ʈ/,/r̲/	Stop	100
/k/	I	2	/g/,/t/	Stop	100	0			
	M	3	/t/	Stop	100	3	/t/	Stop	100
/kʰ/	I		NT			11	/k/,/g/ /t/ /h/	Stop Fricative	72.72 27.27
	M		NT			12	/k/	Stop	100

Note. NPS-Number of participants with substitution error, PPS(%)- Percentage of participants with substitution error, PS- phonemes substituted, MOA- manner of articulation, I- initial, M-medial, NT-Not tested

Table 4.61

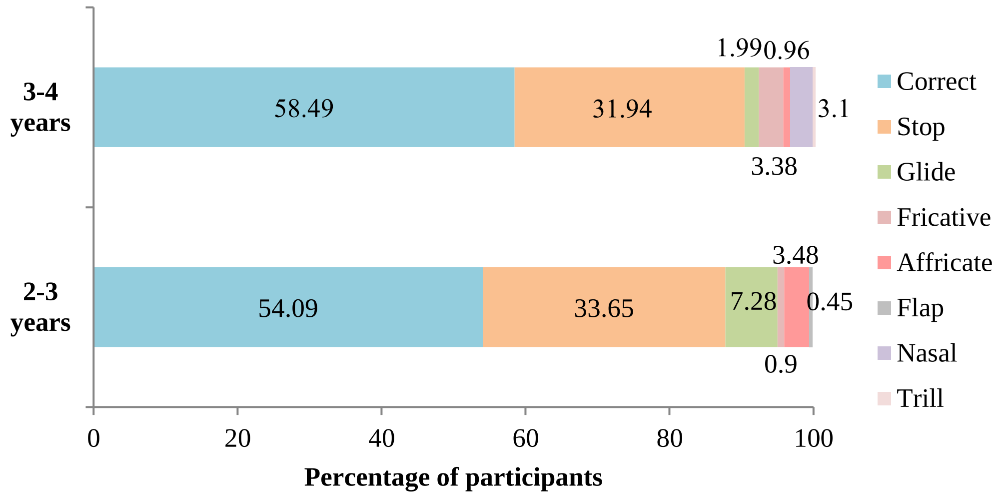
Substitution Errors of Voiced Stops in Children with 2-3 and 3-4 years of CI Experience

Phoneme	Position	2-3 years				3-4 years			
		NPS	PS	MOA	PPS (%)	NPS	PS	MOA	PPS (%)
/b/	I	10	/p/ /v/ /f/	Stop Glide Fricative	80 10 10	6	/p/ /m/	Stop Nasal	66.66 33.33
	M	5	/p/ /v/ /f/	Stop Glide Fricative	60 20 20	3	/p/	Stop	100
/b^h/	M	NT				12	/p/ /v/	Stop Glide	75 25
/d/	I	5	/k/,/t/ /j/ /c/	Stop Glide Affricate	60 20 20	4	/ʈ/,/ɖ/ /j/	Stop Glide	75 25
	M	3	/j/ /t/	Glide Stop	66.66 33.33	6	/ʈ/,/ɖ/ /m/ /j/	Stop Nasal Glide	50 33.33 16.66
/d^h/	M	NT				15	/d/,/t/ /l/	Stop Lateral	80 20
/ɖ/	I	11	/ʈ/,/t/, /d/,/k, /g/	Stop	100	6	/ʈ/,/d/ /j/	Stop Glide	83.33 16.66
	M	10	/ʈ/,/t/ /d/,/g/ /r/ /j/	Stop Flap Glide	70 10 20	8	/ʈ/,/d/ /ṛ/	Stop Trill	87.5 12.5
/g/	I	9	/k/,/t/ /d/,/ɖ/ /j/, /v/	Stop Glide	77.77 22.22	8	/k/,/t/ /d/ /n̪/,/ɳ/	Stop Nasal	75 25
	M	4	/k/,/t/ /d/	Stop	100	4	/k/,/t/	Stop	100
/g^h/	M	NT				12	k h	Stop Fricative	25 75

Note. NPS-Number of participants with substitution error, PPS(%)- Percentage of participants with substitution error, PS- phonemes substituted, MOA- manner of articulation, I- initial, M-medial, NT-Not tested

Figure 4.41

Percentage of Participants with Correct Production and Substitution Errors of Stops in Children with 2-3 and 3-4 years of CI Experience



2. Nasals.

Nasals tested in the initial position include /m/, dental /n/ and palatal /ɲ/. All the nasals were tested in the medial position and alveolar /n/, retroflex /ɳ/, and bilabial /m/ were tested in the final position.

SODA Analysis: Percentage of correct production, substitution, omission, distortion and addition errors of nasals in both subgroups of children using CI are shown in Table 4.62. Substitutions were the most common type of error observed in nasals and the percentage of substitutions reduced in children with greater implant experience. Among nasals, bilabial nasal /m/ was the most correctly produced irrespective of the phoneme position and implant experience of the participants. Palatal /ɲ/, retroflex /ɳ/ and alveolar /n/ were the most difficult phoneme in initial, medial, and final positions respectively. The percentage of correct production of nasals across phoneme positions was examined and accuracy was found to be higher in medial position for dental /n̪/, alveolar /n/, and palatal /ɲ/. Retroflex /ɳ/ had better production in final position whereas the production accuracy was similar in all positions for bilabial /m/. The improvement in phoneme production with increase in implant experience in initial, medial and final positions are represented in Figures 4.42, Figure 4.43 and Figure 4.44 respectively. From the figures, it could be observed that accuracy of production increased with increase in implant experience.

Figure 4.42

Percentage of Participants with Correct Production of Nasals in Word-Initial Position with 2-3 and 3-4 years of CI Experience

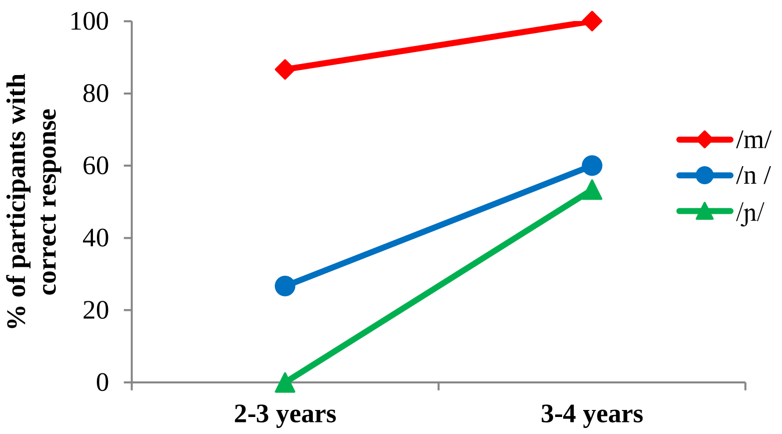


Figure 4.43

Percentage of Participants with Correct Production of Nasals in Word-Medial Position with 2-3 and 3-4 years of CI Experience

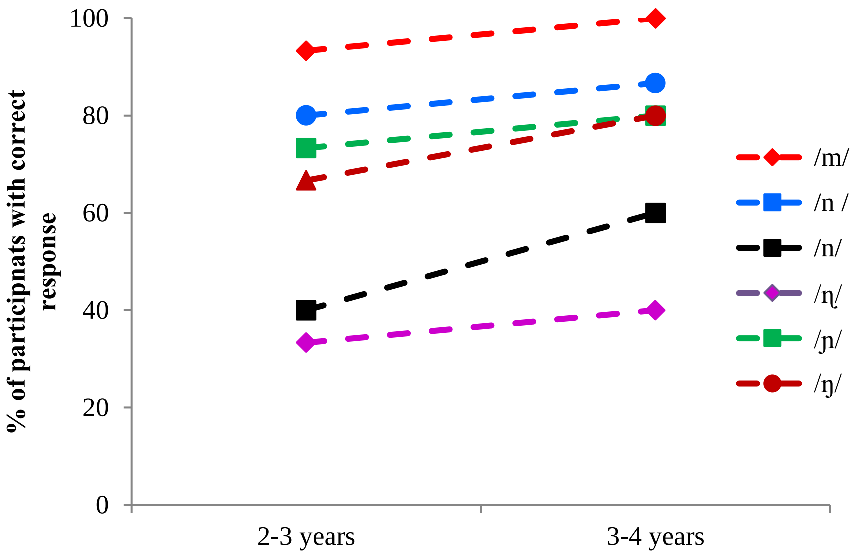


Table 4.62

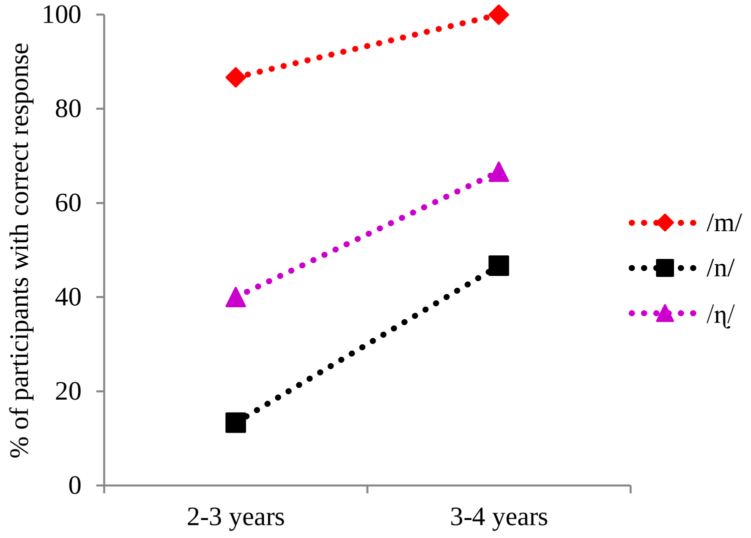
Percentage of Participants Exhibiting SODA Errors for Nasals across Phoneme Position in Children with 2-3 and 3-4 years of CI Experience

Phoneme	Initial				Medial				Final			
	2-3 years		3-4 years		2-3 years		3-4 years		2-3 years		3-4 years	
	CR (%)	Err (%)	CR (%)	Err (%)	CR (%)	Err (%)	CR (%)	Err (%)	CR (%)	Err (%)	CR (%)	Err (%)
/m/	86.66	13.33 (S)	100	0	93.33	6.66 (0)	100	0	86.66	13.33 (0)	100	-
/n̪/	26.66	66.66 (S) 6.66 (O)	60	33.33 (S) 6.66 (O)	80	20 (S)	86.66	6.66 (S) 6.66 (D)	NT		NT	
/n/	NT		NT		40	60 (S)	60	40(S)	13.33	40 (S) 46.66 (O)	46.66	26.66 (S) 26.66 (O)
/ɳ/	NT		NT		33.33	66.66 (S)	40	60(S)	40	40 (S) 20 (O)	66.66	26.66 (S) 6.66 (O)
/ɲ/	0	93.33(S) 6.66 (O)	53.33	40 (S) 6.66 (O)	73.33	20(S) 6.66 (O)	80	20 (S)	NT		NT	
/ŋ/	NT		NT		66.66	33.33 (S)	80	20 (S)	NT		NT	

Note. CR: correct responses, Err: error, S-substitution O- Omission D- Distortion A-Addition, NT-not tested

Figure 4.44

Percentage of Participants with Correct Production of Nasals in Word-Final Position with 2-3 and 3-4 years of CI Experience



Substitution Error Analysis: Analysis of substitution errors of nasals with respect to manner of articulation in both groups of children using CI is shown in Table 4.63. The table describes the number of substitution and the manners of articulation with which a particular phoneme is substituted. From the table it could be observed that nasals were frequently substituted with other nasals, glides, stops and laterals. Substitutions with affricates and flap were also observed in lesser percentage of participants. Percentage of participants with correct production and substitution errors of nasals in both groups of participants using CI is shown in Figure 4.45. Percentage of participants with correct production of nasals increased from 61.18% to 75.29% with increase in CI experience. Children with lesser implant experience used nasal-stop substitutions with an overall percentage of 7%, whereas this pattern of substitutions which was widely reported in literature was completely absent in children with greater implant experience.

Table 4.63

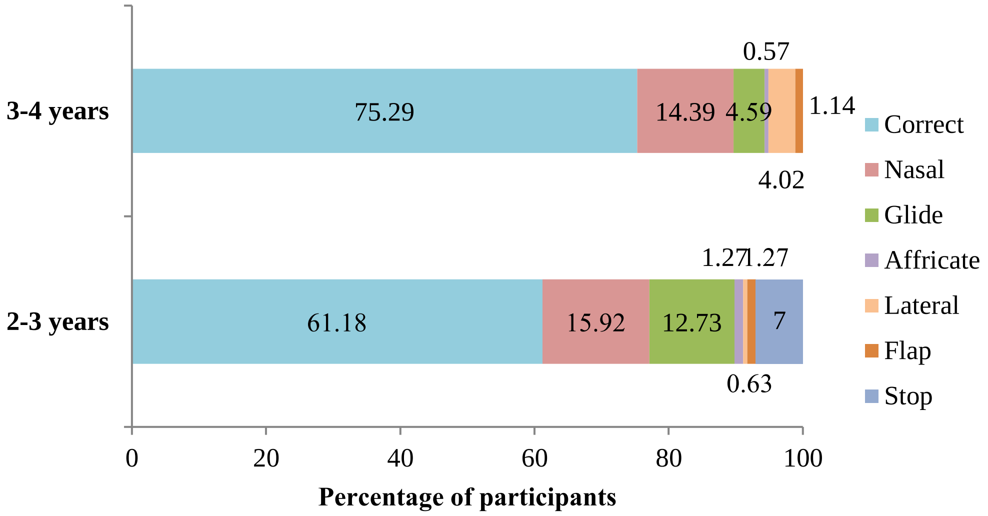
Substitution Errors of Nasals in Children with 2-3 and 3-4 years of CI Experience

Phoneme	Position	2-3 years				3-4 years			
		NPS	PS	MOA	PPS (%)	NPS	PS	MOA	PPS (%)
/m/	I	2	/v/	Glide	100	0	-	-	-
	M	1	/ŋ/	Nasal	100	0	-	-	-
	F	0	-	-	-	0	-	-	-
/n̪/	I	10	/n/,/m/	Nasal	50	5	/n/	Nasal	80
			/p/,/d/	Stop	30		/c/	Affricate	20
			/c/	Affricate	10				
	M	3	/n/,/ɳ/	Nasal	100	1	/ɳ/	Nasal	100
/n/	M	8	/ɲ/	Nasal	12.5	6	/ɲ/	Nasal	16.66
			/g/	Stop	25		/l/	Lateral	50
			/j/	Glide	62.5		/j/	Glide	33.33
	F	6	/m/	Nasal	33.33	4	/ɳ/	Nasal	25
			/l/	Lateral	16.66		/l/	Lateral	50
			/j/	Glide	50		/j/	Glide	25
/ɳ/	M	7	/ɲ/,/n/	Nasal	28.57	10	/ŋ/,/n/	Nasal	50
			/j/	Glide	42.85		/j/	Glide	20
			/r/	Flap	14.28		/l/	Lateral	20
			/g/	Stop	14.28		/r/	Flap	10
	F	3	/n/,/m/	Nasal	100	5	/n̪/,/n/	Nasal	100
/ɲ/	I	14	/j/	Glide	50	6	/n/	Nasal	33.33
			/c/	Affricate	7.14		/j/,/v/	Glide	50
			/t/, /d/	Stop	35.71		/r/	Flap	16.66
			/r/	Flap	7.14				
	M	3	/n/,/ŋ/	Nasal	100	3	/n/,/ɳ/	Nasal	100
/ŋ/	M	5	/n̪/,/n/	Nasal	100	3	/ɳ/,/n/	Nasal	100

Note. NPS-Number of participants with substitution error, PPS(%)- Percentage of participants with substitution error, PS- phonemes substituted, MOA- manner of articulation, I- initial, M-medial, F-final

Figure 4.45

Percentage of Participants with Correct Production and Substitution Errors of Nasals in Children with 2-3 and 3-4 years of CI Experience



3. Fricatives.

Fricatives tested include labiodental /f/, alveolar /s/, retroflex /ʂ/ and palatal /ʃ/. All fricatives were tested in both initial and medial positions except /f/ which was tested in initial position only.

SODA Analysis: Percentage of correct production, substitution, omission, distortion and addition errors of fricatives in both subgroups of children using CI are shown in Table 4.64. Labiodental /f/ was the most correctly produced phoneme in initial position whereas it was palatal /ʃ/ in medial position irrespective of implant experience of the participants. /s/ and /ʂ/ were the most difficult fricatives. Also it could be observed that fricatives were more correctly produced in medial position compared to initial position irrespective of CI experience of the participants. As the duration of implant use increased, the percentage of correct production increased in both initial and medial positions and is depicted in Figure 4.46.

Table 4.64

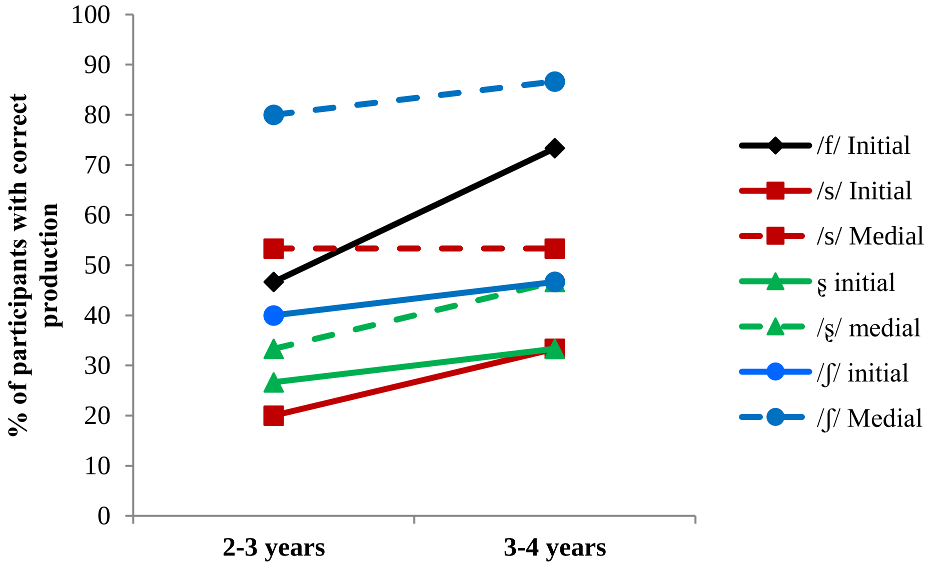
Percentage of Participants Exhibiting SODA Errors for Fricatives across Phoneme Position in Children with 2-3 and 3-4 years of CI Experience

Phoneme	Initial				Medial			
	2-3 years		3-4 years		2-3 years		3-4 years	
	CR (%)	Err (%)	CR (%)	Err (%)	CR (%)	Err (%)	CR (%)	Err (%)
/f/	46.66	53.33 (S)	73.33	26.66 (S)	NT		NT	
/s/	20	80 (S)	33.33	66.66 (S)	53.33	46.66 (S)	53.33	46.66 (S)
/ʂ/	26.66	66.66 (S) 6.66 (O)	33.33	60 (S) 6.66 (D)	33.33	66.66 (S)	46.66	53.33 (S)
/ʃ/	40	60(S)	46.66	40 (S) 13.33 (O)	80	20(S)	86.66	13.33 (S)
/h/	NT		NT		NT		60	40 (O)

Note. CR: correct responses, Err: error, S-substitution O- Omission D- Distortion A-Addition, NT-not tested

Figure 4.46

Percentage of Participants with Correct Production of Fricatives with 2-3 and 3-4 years of CI Experience



Substitution Error Analysis: Analysis of substitution errors of stops with respect to manner of articulation in both groups of children using CI is shown in Table 4.65. Fricatives were predominantly substituted with affricates followed by fricatives and stops. Unvoiced palatal affricate /c/ was the most common substitute for fricatives used by participants irrespective of their implant experience. The next frequently substituted phoneme was palatal fricative /ʃ/. Percentage of participants with correct production and substitution errors of fricatives with respect to manner of articulation in younger and older group of participants is as depicted in Figure 4.47. Percentage of participants with correct productions increased from 46.39% to 56.54% with increase in CI experience. It could be observed that the overall substitution patterns exhibited by both group of participants were similar.

Table 4.65

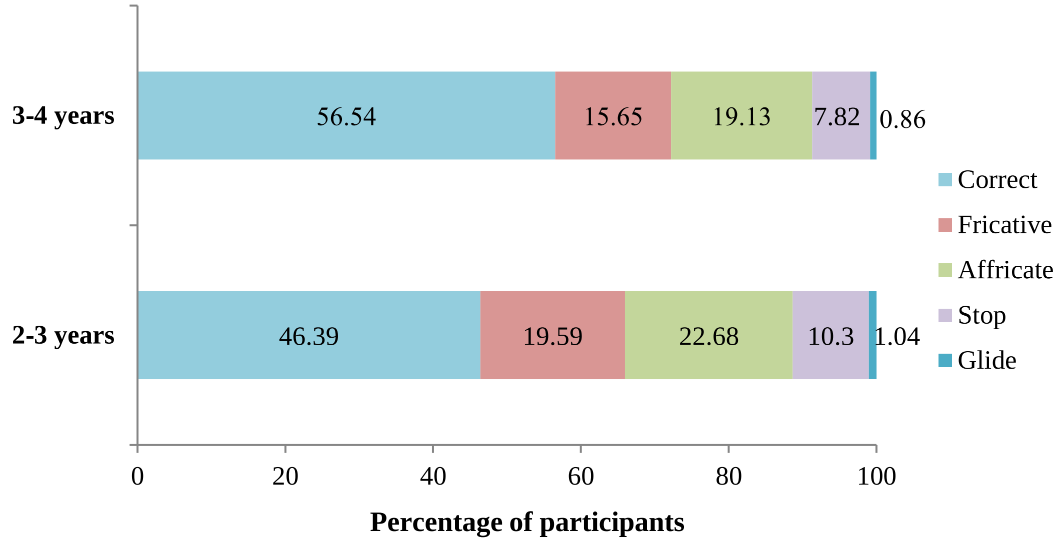
Substitution Errors of Fricatives in Children with 2-3 and 3-4 years of CI Experience

Phoneme	Position	2-3 years				3-4 years			
		NPS	PS	MOA	PPS (%)	NPS	PS	MOA	PPS (%)
/f/	I	7	/s/	Fricative	28.57	9	/ʃ/	Fricative	22.22
			/p/	Stop	57.14		/p/	Stop	66.66
			/c/	Affricate	14.28		/c/	Affricate	11.11
/s/	I	11	/ʃ/	Fricative	18.18	10	/ʃ/	Fricative	20
			/c/	Affricate	72.72		/c/	Affricate	70
			/j/	Glide	9.09		/j/	Glide	10
	M	6	/ʃ/	Fricative	33.33	6	/ʃ/	Fricative	66.66
			/ʂ/				/c/	Affricate	16.66
			/k/	Stop	50		/t/	Stop	16.66
			/c/	Affricate	16.66				
/ʂ/	I	9	/ʃ/	Fricative	55.55	9	/ʃ/	Fricative	33.33
			/s/				/c/	Affricate	44.44
			/c/	Affricate	11.11		/t/	Stop	22.22
			/r̠/	Stop	33.33		/ʈ/		
			/t/						
	M	10	/ʃ/	Fricative	80	8	/ʃ/	Fricative	62.5
			/s/				/s/		
			/c/	Affricate	20		/c/	Affricate	37.5
/ʃ/	I	7	c	Affricate	100	6	/s/	Fricative	33.33
							/c/	Affricate	66.67
	M	2	/c/	Affricate	100	2	/c/	Affricate	100

Note. NPS-Number of participants with substitution error, PPS(%)- Percentage of participants with substitution error, PS- phonemes substituted, MOA- manner of articulation, I- initial, M-medial

Figure 4.47

Percentage of Participants with Correct Production and Substitution Errors of Fricatives in Children with 2-3 and 3-4 years of CI Experience



4. Affricates.

The affricates tested include unvoiced palatal affricates /c/, /c^h/ and its voiced cognate /ɟ/. /c/ and /ɟ/ were tested in both initial and medial positions whereas /c^h/ was tested only in the initial position.

SODA nalysis: Percentage of correct production, substitution, omission, distortion and addition errors of affricates in both subgroups of children using CI are shown in Table 4.66. Unvoiced /c/ was consistently the most correctly produced affricate in all phoneme positions, whereas, voiced palatal affricate /ɟ/ exhibited the least accuracy in all phoneme positions. When the correct productions were compared between phoneme positions, higher percentage of participants produced /c/ correctly in medial position, whereas for /ɟ/ it was in initial position. The percentage of correct production increased with increase in implant experience and the same is depicted in Figure 4.48.

Table 4.66

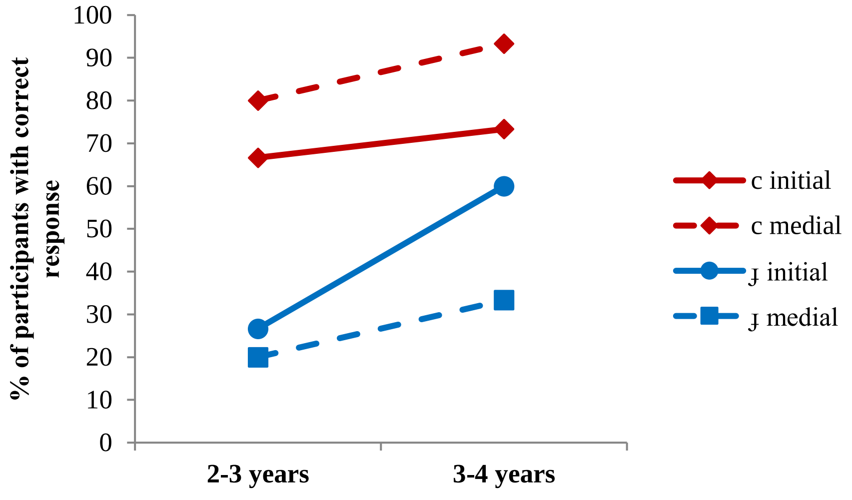
Percentage of Participants Exhibiting SODA Errors for Affricates across Phoneme Position in Children with 2-3 and 3-4 years of CI Experience

Phoneme	Initial				Medial			
	2-3 years		3-4 years		2-3 years		3-4 years	
	CR (%)	Err (%)	CR (%)	Err (%)	CR (%)	Err (%)	CR (%)	Err (%)
/c/	66.66	33.33(S)	73.33	20 (S) 6.66(O)	80	13.33 (S) 6.66(A)	93.33	6.66(D)
/cʰ/	NT		60	40 (S)	NT		NT	
/ɟ/	26.66	73.33 (S)	60	40 (S)	20	80 (S)	33.33	60 (S) 6.66 (D)

Note. CR: correct responses, Err: error, S-substitution O- Omission D- Distortion A-Addition, NT-not tested

Figure 4.48

Percentage of Participants with Correct Production of Affricates with 2-3 and 3-4 years of CI Experience



Substitution Error Analysis: Analysis of substitution errors of affricates with respect to manner of articulation in both groups of children using CI is as shown in Table 4.67. It could be observed that affricates were substituted with affricates, stops, glides, flap and fricatives. Unvoiced affricate /c/ was the most common phoneme substituted for the other two affricates /c^h/ and/ɟ/. Percentage of participants with correct production and substitution errors of affricates in both groups of participants using CI is as shown in Figure 4.49. Percentage of participants with correct productions increased to 65.77% in children with longer CI experience.

Table 4.67

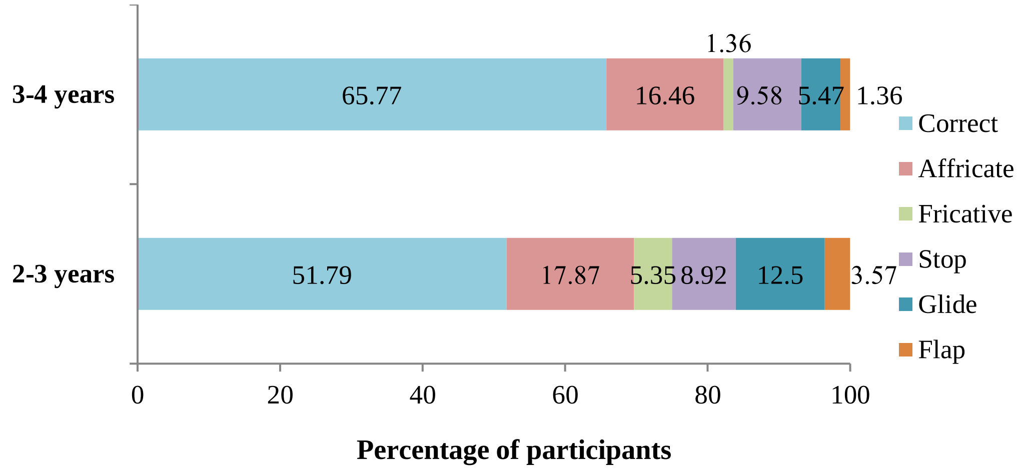
Substitution Errors of Affricates in Children with 2-3 and 3-4 years of CI Experience

Phoneme	Position	2-3 years				3-4 years			
		NPS	PS	MOA	PPS (%)	NPS	PS	MOA	PPS (%)
/c/	I	4	/t/	Stop	75	3	/ɟ/	Affricate	66.66
			/ʃ/	Fricative	25		/ʃ/	Fricative	33.33
	M	2	/ʃ/	Fricative	100	0	-	-	-
/c^h/	I	NT				6	c	Affricate	100
/ɟ/	I	9	/c/	Affricate	77.77	6	/c/,/c^h/	Affricate	33.33
			/j/	Glide	11.11		/t/,/d/	Stop	66.66
			/d/	Stop	11.11		/ʈ/		
	M	12	/c/	Affricate	25	10	/c/	Affricate	20
			/j/,/v/	Glide	50		/j/	Glide	40
			/t/	Stop	8.33		/t/,/d/	Stop	30
			/r/	Flap	16.66		/r/	Flap	10

Note. NPS-Number of participants with substitution error, PPS(%)- Percentage of participants with substitution error, PS- phonemes substituted, MOA- manner of articulation, I- initial, M-medial, NT-Not tested

Figure 4.49

Percentage of Participants with Correct Production and Substitution Errors of Affricates in Children with 2-3 and 3-4 years of CI Experience



5. Approximants.

The approximants studied include glides (palatal /j/ & labiodental /v/), laterals (alveolar /l/ & retroflex /ɭ/), trill (/ṛ/), flap (/r/) and approximant (/ʐ/). Glides and flap /r/ were tested in both initial and medial positions whereas lateral /l/ and trill /ṛ/ in initial, medial and final positions. Retroflex lateral /ɭ/ was tested in medial and final positions and approximant /ʐ/ was tested in medial position only.

SODA Analysis: Percentage of correct production, substitution, omission, distortion and addition errors of approximants in both subgroups of children using CI are as shown in Table 4.68. Among the approximants, glides were the most accurate class of phonemes followed by laterals, flap, trill and retroflex approximant /ʐ/. Palatal glide /j/ had the highest percentage of correct production irrespective of phoneme position and implant experience. Retroflex approximant /ʐ/ was the most difficult of all the phonemes with no improvement with increase in implant experience. On observation it was noted that glide /j/ and lateral /ɭ/ had better production in medial position compared to other positions whereas such a trend was absent for other phonemes. The improvement in accuracy of production with increase in implant experience are depicted in Figure 4.50 (glides), Figure 4.51 (laterals), and Figure 4.52 (trill & flap). From the figure, it could be observed that the accuracy of production increased with increase in implant experience.

Table 4.68

Percentage of Participants Exhibiting SODA Errors for Approximants across Phoneme Position in Children with 2-3 and 3-4 years of CI Experience

Phoneme	Initial				Medial				Final			
	2-3 years		3-4 years		2-3 years		3-4 years		2-3 years		3-4 years	
	CR (%)	Err (%)	CR (%)	Err (%)	CR (%)	Err (%)	CR (%)	Err (%)	CR (%)	Err (%)	CR (%)	Err (%)
/j/	66.66	26.66(S) 6.66 (O)	80	13.33 (S) 6.66 (O)	73.33	13.33 (S) 13.33(O)	93.33	6.66 (S)	NT		NT	
/v/	60	40 (S)	73.33	20 (S) 6.66 (D)	60	40 (S)	80	20 (S)	NT		NT	
/l/	33.33	60 (S)	66.66	33.33 (S)	33.33	53.33 (S) 6.66 (O)	73.33	20(S) 6.66 (O)	53.33	26.66 (S) 20 (O)	73.33	13.33 (S) 13.33 (O)
/ɭ/	NT		NT		66.66	33.33(S)	73.33	26.66 (S)	40	53.33 (S) 6.66 (O)	53.33	40 (S) 6.66 (O)
/ṛ/	20	80 (S)	26.66	46.66 (S) 20 (O) 6.66 (D)	6.66	26.66 (S) 60 (O) 6.66 (D)	40	53.33 (S) 6.66 (O)	20	20(S) 40 (O) 20 (D)	33.33	40 (S) 13.33 (O) 13.33 (D)
/r/	20	80 (S)	33.33	53.33 (S) 13.33 (D)	13.33	33.33 (S) 33.33 (O) 20 (D)	46.66	33.33 (S) 20 (O)	NT		NT	
/ʐ/	NT		NT		0	100(S)	0	80(S) 20(O)	NT		NT	

Note. CR: correct responses, Err: error, S-substitution O- Omission D- Distortion A-Addition, NT-not tested

Figure 4.50

Percentage of Participants with Correct Production of Glides with 2-3 and 3-4 years of CI Experience

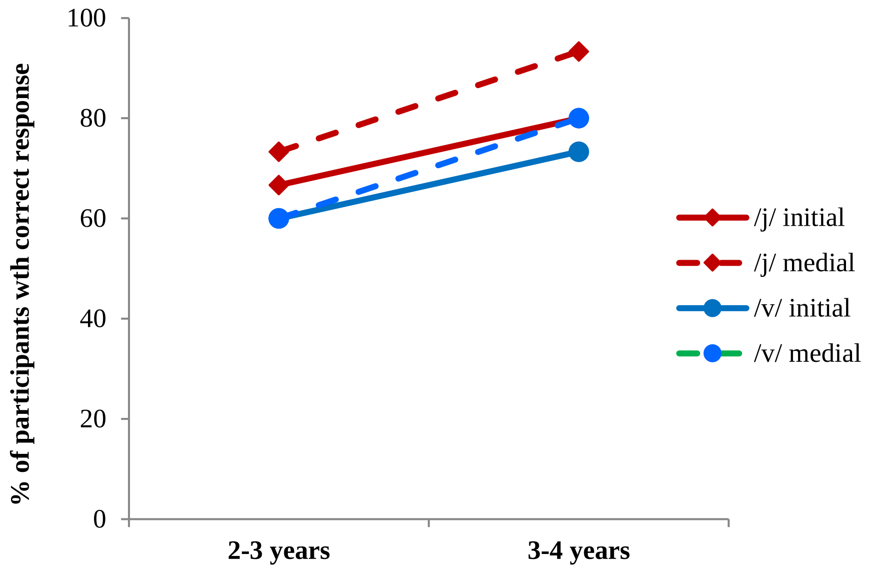


Figure 4.51

Percentage of Participants with Correct Production of Laterals with 2-3 and 3-4 years of CI Experience

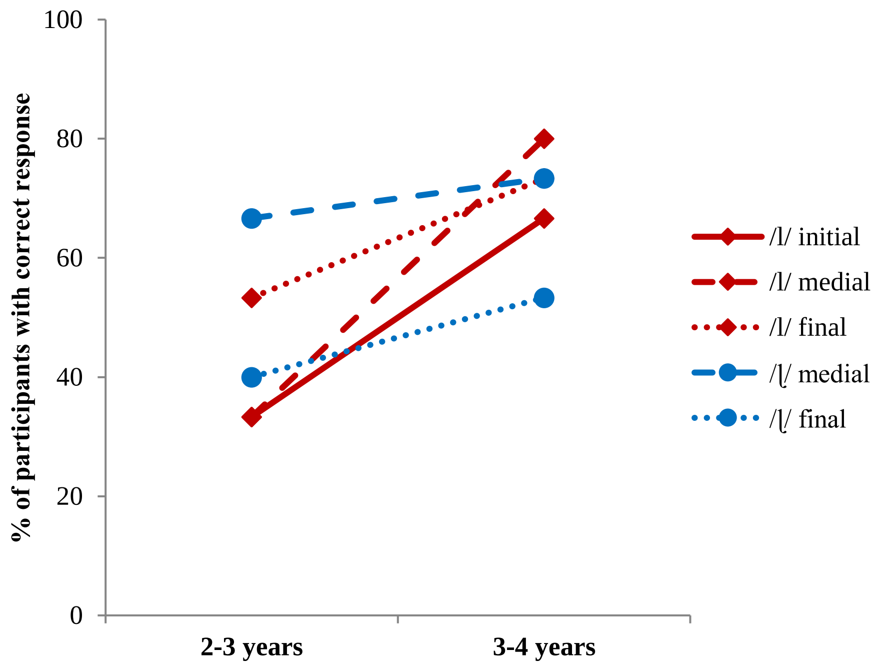
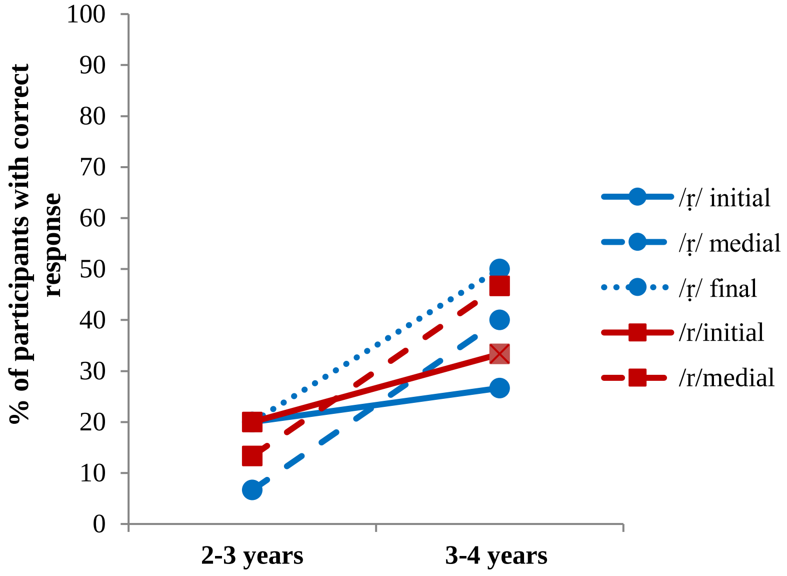


Figure 4.52

Percentage of Participants with Correct Production of Trill and Flap with 2-3 and 3-4 years of CI Experience



Substitution Error Analysis: Substitution errors of approximants were analyzed with respect to manner of articulation and are discussed separately under three sections namely glides, laterals, and trill, flap, approximant for ease of understanding. Analysis of substitution errors of glides with respect to manner of articulation in both groups of children using CI is as shown in Table 4.69. The number of participants with substitution reduced to about half in older group of participants. /v/ was predominantly substituted with bilabial stops irrespective of phoneme position and CI experience. Percentage of participants with correct production and substitution errors of glides in both groups of participants using CI is as shown in Figure 4.53. Glides were predominantly substituted with stops, affricates, glide and lateral in children with lesser implant experience. This variability of substitution with multiple classes of phonemes reduced to stops and laterals in participants with longer duration of implant use.

Table 4.69

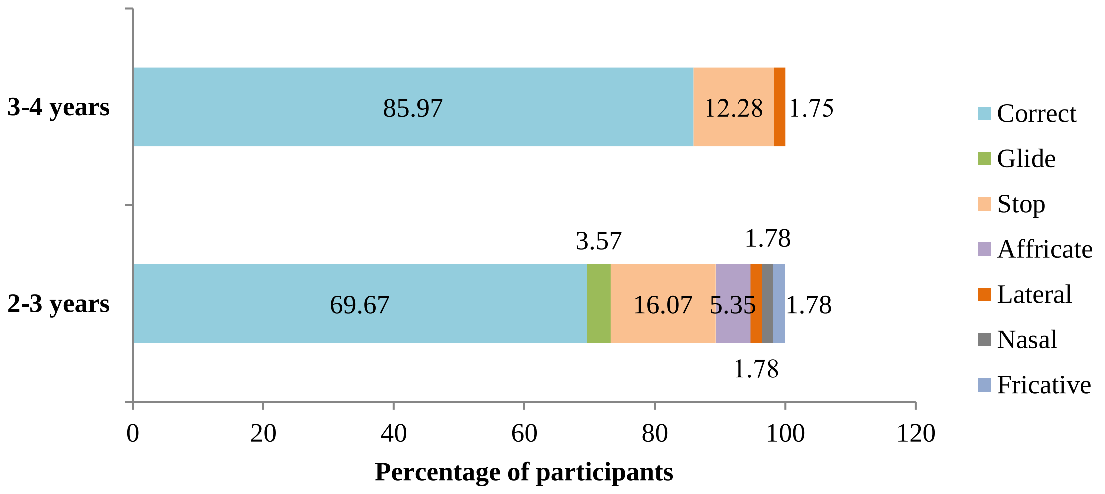
Substitution Errors of Glides in Children with 2-3 and 3-4 Years of CI Experience

Phoneme	Position	2-3 years				3-4 years			
		NPS	PS	POA	PPS (%)	No of sub	PS	POA	PPS (%)
/j/	I	4	/c/ /ɲ/	Affricate Nasal	75 25	1	/t/	Stop	100
	M	2	/ʃ/ /l/	Fricative Lateral	50 50	1	/l/	Lateral	100
/v/	I	5	/b/	Stop	100	3	/b/,/p/	Stop	100
	M	6	/b/,/d/ /j/	Stop Glide	66.66 33.33	3	/b/	Stop	100

Note. NPS-Number of participants with substitution error, PPS(%)- Percentage of participants with substitution error, PS- phonemes substituted, MOA- manner of articulation, I- initial, M- medial, F-final

Figure 4.53

Percentage of Participants with Correct Production and Substitution Errors of Glides in Children with 2-3 and 3-4 years of CI Experience



Analysis of substitution errors of laterals with respect to manner of articulation in both subgroups of children using CI is shown in Table 4.70. It could be observed that laterals were frequently substituted with other laterals, glides and nasals by both groups of participants. Percentage of participants with correct production and substitution errors of laterals in both groups of participants using CI is shown in Figure 4.54. Percentage of participants with correct production increased from 52.33% to 71.86% with increase in duration of CI use. From the figure it was evidenced that, with increase in duration of implant use, higher percentage of participants substituted lateral with a lateral itself (18.46% to 11.26%). Lateral-glide substitution decreased (20% to 4.22%) in older group of participants whereas lateral-nasal substitution increased (4.61% to 7.04%).

Table 4.70

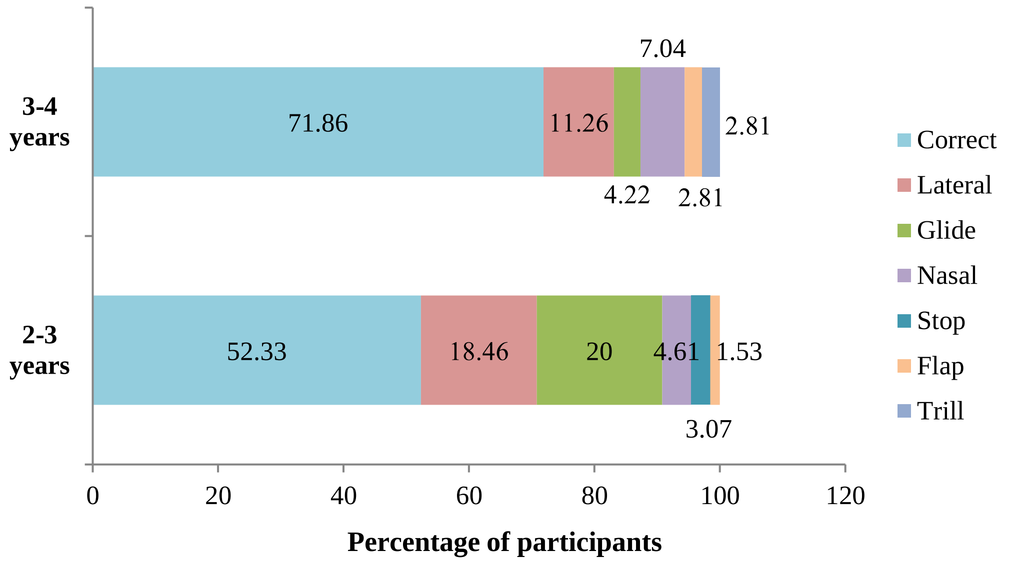
Substitution Errors of Laterals in Children with 2-3 and 3-4 years of CI Experience

Phoneme	Position	2-3 years				3-4 years			
		No. of sub	PS	POA	PPS (%)	No of sub	PS	POA	PPS (%)
/l/	I	7	/j/	Glide	57.14	4	/r/	Flap	25
			/ɭ/	Lateral	28.57		/ṛ/	Trill	50
			/d/	Stop	14.28		/d/	Stop	25
	M	7	/ɭ/	Lateral	42.85	3	/n/	Nasal	33.33
			/ɖ/	Stop	14.28		/r/	Flap	33.33
			/j/	Glide	28.57		/j/	Glide	33.33
			/n/	Nasal	14.28				
	F	4	/j/	Glide	50	2	/n/	Nasal	100
			/r/	Flap	25				
			/n/	Nasal	25				
/ɭ/	M	5	/j/	Glide	60	4	/l/	Lateral	100
			/n/	Nasal	20				
			/l/	Lateral	20				
	F	8	/l/	Lateral	87.5	7	/l/	Lateral	57.14
			/j/	Glide	12.5		/ɳ/	Nasal	28.57
							/j/	Glide	14.28

NPS-Number of participants with substitution error, PPS(%)- Percentage of participants with substitution error, PS- phonemes substituted, MOA- manner of articulation, I- initial, M-medial, F-final

Figure 4.54

Percentage of Participants with Correct Production and Substitution Errors of Laterals in Children with 2-3 and 3-4 years of CI Experience



Analysis of substitution errors of trill, flap and approximant with respect to manner of articulation in both groups of children using CI is as shown in Table 4.71. Frequent substitutions observed in this group of phonemes were with glides, laterals and stops in both groups of participants. Though occasionally, substitution of flap /r/ with trill /ṛ/ was observed in older group of participants only indicating a more developmentally appropriate trend. Retroflex approximant /z̢/ was substituted with glide /j/ and lateral /l/ irrespective of implant experience of participants. Percentage of participants with correct production and substitution errors of trill, flap and approximant /z̢/ in both groups of participants using CI is as shown in Figure 4.55.

Table 4.71

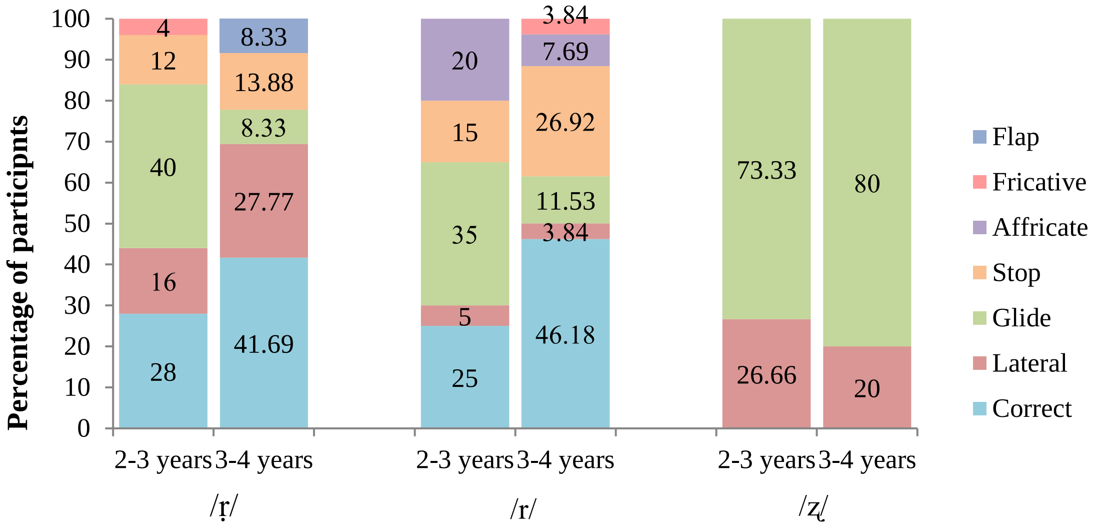
Substitution Errors of Trill, Flap and Approximant /ʐ/ in Children with 2-3 and 3-4 years of CI Experience

Phoneme	Position	2-3 years				3-4 years			
		NPS	PS	MOA	PPS (%)	NPS	PS	MOA	PPS (%)
/R/	I	11	/s/	Fricative	9.09	7	/j/	Glide	42.85
			/j/	Glide	81.81		/g/,/t/	Stop	42.85
			/ʈ/	Stop	9.09		/r/	Flap	14.28
	M	4	/ɖ/	Stop	50	8	/ɖ/	Stop	25
			/ɭ/	Lateral	50		/ɭ/	Lateral	50
							/r/	Flap	25
	F	3	/ɭ/	Lateral	66.66	6	/ɭ/,/l/	Lateral	100
			/v/	Glide	33.33				
/r/	I	11	/c/	Affricate	36.36	8	/s/	Fricative	12.5
			/j/,/v/	Glide	45.45		/l/	Lateral	12.5
			/t/,/g/	Stop	18.18		/ʈ/,/ɖ/	Stop	37.5
							/c/	Affricate	25
							/j/	Glide	12.5
	M	4	/j/	Glide	50	5	/d/,/ɖ/	Stop	60
			/l/	Lateral	25		/j/	Glide	40
			/ɖ/	Stop	25				
/ʐ/	M	15	/j/	Glide	73.33	15	/j/	Glide	80
			/l/	Lateral	26.66		/l/	Lateral	20

Note. NPS-Number of participants with substitution error, PPS(%)- Percentage of participants with substitution error, PS- phonemes substituted, MOA- manner of articulation, I- initial, M-medial

Figure 4.55

Percentage of Participants with Correct Production and Substitution Errors of Trill, Flap and Approximant /ʐ/ in Children with 2-3 years of CI Experience



4.2.2.2.3. Voicing Feature Analysis.

Voicing feature was analyzed only for those phonemes with voiced-unvoiced cognates. Therefore, stops and affricates were only considered for this analysis. Percentage of participants who produced voicing feature correctly was calculated considering both correct productions and substitution errors. Correctness of place and manner features was not considered for this analysis. For e.g. if /g/ is substituted with /d/, then the production of voicing is correct even though there is error in place of articulation (velar with dental). Table 4.72 shows the percentage of participants who correctly produced voicing feature in both groups of children using CI. From the table it could be observed that voiced phonemes exhibited more errors with respect to voicing compared to unvoiced phonemes for both stops and affricates. Voiced aspirated phonemes demonstrated more devoicing errors compared to their unaspirated cognates. With increase in CI experience, voicing errors reduced for both voiced and unvoiced phonemes. However it could be observed that devoicing of voiced phonemes persisted even after 3-4 years of CI use, though there was considerable improvement seen in unvoiced phonemes as depicted in figure 4.56.

Table 4.72

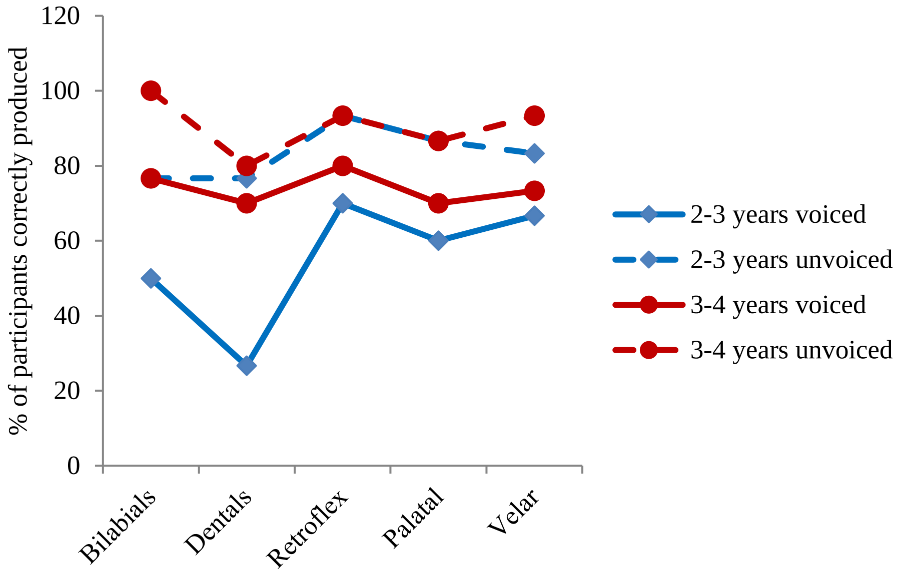
Percentage of Participants Correctly Produced Voicing Feature in Children with 2-3 and 3-4 years of CI Experience

MOA	POA	Voiced			Unvoiced		
		Phoneme	2-3 years	3-4 years	Phoneme	2-3 years	3-4 years
Stops	Bilabial	/b/	50	76.66	/p/	76.66	100
		/bʰ/		40			
	Dental	/d/	26.66	70	/t/	76.66	80
		/dʰ/		80	/tʰ/		80
	Alveolar				/r̠/	100	93.33
	Retroflex	/ɖ/	70	80	/ʈ/	93.33	93.33
					/ʈʰ/		100
	Velar	/g/	66.66	73.33	/k/	83.33	93.33
		/gʰ/		20	/kʰ/		90
Affricates	Palatal	/ɟ/	60	70	/c/	86.66	86.66
					/cʰ/		100

Note. POA-place of articulation.

Figure 4.56

Overall Substitution Patterns of Voiced and Unvoiced Phonemes across POA in Children with 2-3 and 3-4 years of CI Experience



Overall SODA analysis of consonant errors showed that majority were substitution errors followed by omissions, distortions and additions. With increase in duration of implant use, percentage of correct production of consonants increased and the overall percentage of consonant substitution errors reduced. Percentage of correct production and overall SODA errors of both groups of participants of CI is as shown in Figures 4.57 and Figure 4.58.

Figure 4.57

Percentage of Correct Production and Overall SODA Errors in Children with 2-3 years of CI Use

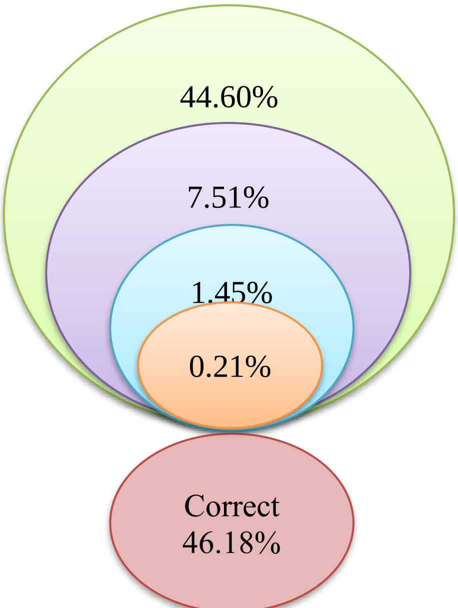
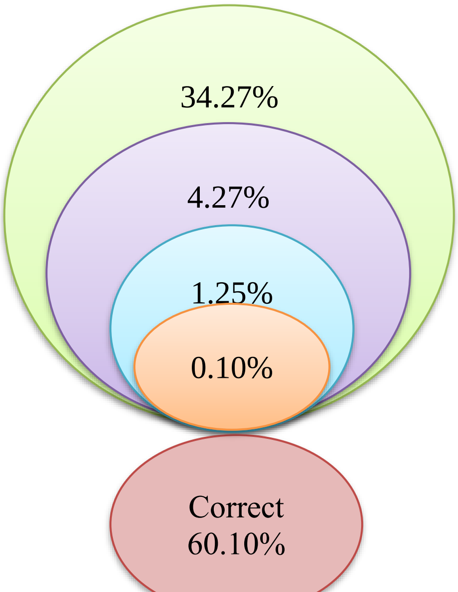


Figure 4.58

Percentage of Correct Production and Overall SODA Errors in Children with 3-4 years of CI Use



4.2.2.2.4. Summary of Qualitative Analysis of Consonants

a. Place of Articulation

Bilabials: Among bilabials, /m/ was the most correctly produced and /b/ was the least in both groups of participants of CI. Bilabials were most frequently substituted with other bilabials in both subgroups of CI. There was no common phoneme position that facilitated the correct production of bilabials. As the implant experience of participants increased, variability in class of phonemes with which the phoneme was substituted reduced.

Labiodentals: In participants with lesser CI experience, majority of participants produced /v/ more correctly compared to /f/, whereas those with longer CI experience had comparable scores for /f/ and /v/. Medial position facilitated the production of /v/ in younger group of participants. However such a trend was not present for older group of participants. Bilabial stops /p/ and /b/ were the most common phonemes substituted for labiodentals by the participants irrespective of implant experience and phoneme position.

Dentals: Dental stops had better produced in initial position compared to medial position whereas, for nasal /n̪/ it was in medial position. /d/ was the most difficult phoneme among dentals in initial as well as medial positions in both groups of participants.

Alveolars: Lateral /l/ showed the highest improvement in accuracy of production in initial and final positions irrespective of implant experience. /ṛ/ and /r/ were the most difficult phonemes among alveolars irrespective of phoneme position and implant experience of the participants. Alveolars were substituted with a variety of places of articulation except glottals, especially in younger group of participants and this variability reduced with CI experience.

Retroflex: Unvoiced retroflex stop /ʈ/ and lateral /ɭ/ had the highest accuracy in initial and medial positions respectively in both subgroups of CI. It was also interesting to note that retroflex approximant /ʐ/ was the most difficult phoneme and was not produced correctly by any of the participants in both groups. Retroflex phonemes were substituted with multiple phoneme classes in younger group of participants and this variability did not reduce considerably with increase in implant experience.

Palatals: Affricate /c/ and glide /j/ were the most correctly produced phonemes in initial and medial position by both group of participants. The only exception to this trend was that /c/ and /ʃ/ were the most accurate phonemes in medial position for younger group of participants. Nasal /ɲ/ was the most difficult phoneme in the initial position for younger group of participants and voiced affricate /ɟ/ was the most difficult phoneme in the medial position irrespective of implant experience of the participants.

Velars and Glottals: Unvoiced stop /k/ had the highest accuracy and voiced /g/ had the least accuracy in both subgroups of CI irrespective of phoneme position.

Overall it was noted that percentage of participants with correct productions increased considerably with increase in CI experience. Bilabials were the most correctly produced place by maximum percentage of participants and retroflex were the lowest in both sub groups of CI. The order of accuracy of different places of articulation was as follows: Retroflex < alveolar < dental < labiodental < palatals < velars<bilabials. Table 4.73 represents the most correctly /incorrectly produced phoneme by participants in each

phoneme position with respect to places of articulation.

Table 4.73

Most Correctly /Incorrectly Produced Phoneme by CI Participants in each Phoneme Position with respect to Places of Articulation

Places of articulation	Most correctly produced phonemes by participants			Most incorrectly produced phonemes by participants		
	Initial	Medial	Final	Initial	Medial	Final
Bilabials	/m/	/m/	NT	/b/	/b/	NT
Labiodental	/v/	NT	NT	/f/	NT	NT
Dentals	/t/	/n̪/	NT	/d/	/d/	NT
Alveolars	/l/	No trend	/l/	/ṛ/	/ṛ/	/ṛ/
Retroflex	/ʈ/	/ɭ/	/ɳ/	/ʂ/	/ʐ/	/ɭ/
Palatals	/j/	/c/, /j/	NT	/ʃ/, /ɟ/	/ɟ/	NT
Velars and glottals	/k/	/k/	NT	/g/	/g/	NT

Note: NT-Not tested

b. Manner of Articulation

Stops: Among stops, /p/ was most accurately produced by majority of the participants and exhibited the highest accuracy percentage irrespective of the phoneme position and implant experience of the participants. In general, unvoiced stops were produced correctly by greater percentage of participants compared to their voiced cognates. Stops were predominantly substituted with other stops, glides and nasals.

Nasals: Among the nasals, bilabial nasal /m/ was the most correctly produced phoneme irrespective of the phoneme position and implant experience of the participants. Palatal /ɲ/, retroflex /ɳ/ and alveolar /n/ were the most difficult phoneme in initial, medial, and final positions respectively. Nasals were frequently substituted with nasals, glides, stops and laterals.

Fricatives: Initial position facilitated the production of labiodental /f/ was whereas it was medial position for palatal /ʃ/ irrespective of implant experience of the participants. /s/ and /ʂ/ were the most difficult fricatives. Also, fricatives were more accurately produced in medial position compared to initial position irrespective of the implant experience of the participants. Fricatives were predominantly substituted with affricates followed by fricatives and stops. Unvoiced palatal affricate /c/ was the most common substitute for fricatives used by participants irrespective of their implant experience.

Affricates: Unvoiced /c/ was consistently the most accurately produced affricate in all phoneme positions, whereas, voiced palatal affricate /ɟ/ was the least accurate in all phoneme positions by majority of participants. When the correct productions were compared between phoneme positions, higher percentage of participants produced /c/ correctly in medial position and /ɟ/ it was in initial position. Most common substitutions of affricates were with affricates, stops, glides, flap and fricatives. Unvoiced affricate /c/ was the most common phoneme substituted for the other two affricates /c^h/ and/ɟ/.

Approximants: Among the approximants, glides were the most accurate class of phonemes followed by laterals, flap, trill and retroflex approximant. Palatal glide /j/ had the highest percentage of correct production irrespective of phoneme position and implant experience. Retroflex approximant /ʐ/ was the most difficult of all the phonemes with no improvement in accuracy with increase in implant experience. On observation it was noted that glide /j/ and lateral /ɭ/ had better production in medial position compared to other positions whereas such a trend was absent for other phonemes.

Glides were predominantly substituted with stops, affricates, glide and lateral in children with lesser implant experience. This variability of substitution with multiple classes of phonemes reduced to stops and laterals in participants with longer duration of implant use. Laterals were frequently substituted with laterals, glides and nasals by both groups of participants. Trills and flaps were most commonly substituted with glides, laterals and stops in both groups of participants. Retroflex approximant /ʐ/ was substituted with glide /j/ and lateral /l/ irrespective of implant experience of participants.

To summarize, it could be noted that, among manners of articulation, glides were the most correctly produced class of phoneme by maximum percentage of participants and approximant /ʐ/ had the lowest in both sub groups of CI. The order of accuracy of different manners of articulation was as follows: /ʐ/< trill/flap < fricative <affricate<stops<laterals<nasals<glides. Table 4.74 represents the most correctly /incorrectly produced phoneme by participants in each phoneme position with respect to manners of articulation.

Table 4.74

Most Correctly/Incorrectly Produced Phoneme by CI Participants in each Phoneme Position with respect to Manners of Articulation.

Manners of articulation	Most correctly produced phonemes by participants			Most incorrectly produced phonemes by participants		
	Initial	Medial	Final	Initial	Medial	Final
Stops	/p/	/p/	NT	/d/	/d/	NT
Nasals	/m/	/m/	/m/	/ɲ/	/ɳ/	/n/
Fricatives	/f/	/ʃ/	NT	/s/, /ʂ/	/ʂ/	NT
Affricates	/c/	/c/	NT	/ɟ/	/ɟ/	NT

Manners of articulation	Most correctly produced phonemes by participants			Most incorrectly produced phonemes by participants		
	Initial	Medial	Final	Initial	Medial	Final
Approximants	/j/	/j/	/l/	/ṛ/	/ʐ/	/ṛ/

c. Voicing Feature

Voiced phonemes exhibited more errors with respect to voicing compared to unvoiced phonemes for both stops and affricates. Voiced aspirated phonemes demonstrated more devoicing errors compared to their unaspirated cognates. With increase in CI experience, voicing errors reduced for both voiced and unvoiced phonemes. However it could be observed that devoicing of voiced phonemes persisted even after 3-4 years of CI use, though there was considerable improvement seen in unvoiced phonemes. Table 4.75 represents the most correct/incorrectly produced voiced/unvoiced phonemes

Table 4.75

Most Correct/Incorrectly Produced Voiced/Unvoiced Phonemes in Children with 2-3 and 3-4 years of CI Experience

Most correctly produced phoneme by participants	Voiced	/ɖ/
	Unvoiced	/p/
Most incorrectly produced phoneme by participants	Voiced	/ɟ/, /d/
	Unvoiced	/t/

Note. Voicing feature was analyzed only for stops and affricates

4.2.3. Consonant Clusters

MAT-R tests for 30 clusters in word-initial and medial positions (15 each). As the articulation test was administered according to the chronological age of participants, number of clusters tested for younger group of participants were lesser compared to older group. Cluster productions of the participants were subjected to quantitative and qualitative analyses and are discussed separately. For quantitative analysis, initial clusters were divided into clusters with fricatives (e.g. /sk-/, /sp-/), laterals (/gɭ-/, /pɭ-/), and trills (e.g. tṛ -/, /bṛ -/), and glides (e.g. /kj-/) clusters and medial clusters were classified into clusters with fricatives, trills/glides and nasals (e.g. /-nr̠/, /-nt/). Accuracy of cluster production was measured by calculating percentage of correct production for initial and medial clusters and its sub types.

For qualitative analysis, initial clusters were divided into clusters with fricative (/s/), laterals, trill/flap and glide clusters. Medial clusters were divided into clusters with fricatives, trill/flaps, glides, nasals and /ʂ/ clusters. Few additional types of clusters were included here considering the constituent phonemes for better representation of errors. Greenlee's stages of cluster acquisition were used to classify the cluster productions into correct production, cluster simplification, cluster reduction and cluster omission. Cluster reduction errors were further classified into C_1/C_2/C_3 deletions and coalescence errors. Percentage of each of these productions were computed and tabulated for both subgroups of children using CI (2-3 & 3-4 years of CI experience).

4.2.3.1. Quantitative Analyses.

Percentage of consonant clusters correct (PCCC) was calculated for initial and medial clusters and their sub types separately. Mann-Whitney U test was employed for between age group comparison (2-3 vs 3-4 years of CI experience) in children using CI.

Mean, standard deviation, median, inter quartile range and results of Mann-Whitney U test of various measures of cluster production in between children with 2-3 and 3-4 years of CI experience are provided in Table 4.76.

Table 4.76

Mean, Standard Deviation, Median, Inter Quartile Range and Results of Mann-Whitney U Test for Comparison of PCCC scores between Children with 2-3 and 3-4 years of CI Experience

	Cluster type	2-3 years				3-4 years				|z|	*p*	*r*
		Mean	SD	Md	IQR	Mean	SD	Md	IQR			
Initial	Fricatives	11.11	24.12	0.00	0.00	43.33	34.68	25.00	50.00	2.96	0.00**	0.54
	Laterals	17.67	25.70	0.00	25.00	35.00	33.81	25.00	75.00	1.35	0.18	0.25
	Trills/ glides	23.89	23.33	33.33	33.33	47.62	19.96	42.86	28.57	2.41	0.02*	0.44
	Total	14.67	14.45	11.11	30.00	42.67	19.49	40.00	33.33	3.65	0.00**	0.67
Medial	Fricatives	13.33	30.34	0.00	0.00	28.33	31.15	25.00	50.00	1.66	0.10	0.30
	Trills/ glides	19.44	30.16	0.00	33.33	53.33	20.85	50.00	25.00	3.23	0.00**	0.59
	Nasals	33.33	26.73	33.33	33.33	65.71	24.63	71.43	28.57	3.11	0.00**	0.57
	Total	27.74	16.28	28.57	21.79	50.67	15.90	53.33	20.00	3.22	0.00**	0.59

Note. SD-standard deviation, Md- median, IQR- inter-quartile range, *r*-effect size

*p<0.05, **p<0.01

From Table 4.76 it could be noted that younger children using CI were able to produce about 11% of the initial clusters correctly and the accuracy of production increased significantly (|z|=3.65, *p*<0.01, *r*=0.67) in children with longer implant experience (40%). PCCC scores of medial cluster production increased significantly (|z|=3.22, *p*<0.01, *r*=0.59) from 28% to 53% with increase in duration of CI experience. Among initial clusters, fricative (|z|=2.96, *p*<0.01, *r*=0.54) and tril/glide clusters (|z|=2.41, *p*<0.05, *r*=0.44) showed significant improvement in correct productions with increase in implant experience. Among medial clusters, trill/glide clusters (|z|=3.23, *p*<0.01, *r*=0.59) and nasal clusters (|z|=3.11, *p*<0.01, *r*=0.57) showed significant improvement in accuracy as the implant experience increased. Medial clusters were produced with greater accuracy compared to initial clusters in both younger and older groups of children using CI. Among initial clusters, trill/glide clusters had the highest accuracy for both younger and older group of participants and in medial position, it was nasal clusters.

Single sample Wilcoxon signed rank test was employed to compare PCCC scores between clinical and control groups. Cluster production errors were negligible in TDC and their median values were 100. The results indicated that the percentage of correct production of all sub types of clusters in children using CI were significantly lower compared to TDC (p<0.01) as shown in Table 4.77. The table represents the participants with respect to the chronological age of participants in CI and TDC group. It has to be noted that younger group of participants (4.00-5.11 years) in CI group are with 2-3 years of CI experience and older group (6.00-7.11 years) are with 3-4 years of CI experience.

Table 4.77

Results of Single Sample Wilcoxon Signed Rank Test for Comparison of PCCC scores between CI and TDC Groups

Position	Cluster	CI vs TDC	CI vs TDC

	type	(4.0-5.11 years)	(6.0-7.11 years)
		p	*p*
Initial	Fricatives	0.00**	0.00**
	Laterals	0.00**	0.00**
	Trills & glides	0.00**	0.00**
	Total	0.00**	0.00**
Medial	Fricatives	0.00**	0.00**
	Trills & glides	0.00**	0.00**
	Nasals	0.00**	0.00**
	Total	0.00**	0.00**

$^{**}p<0.01$

4.2.3.2. Qualitative Analysis.

Cluster errors were qualitatively analyzed to identify the error patterns of initial and medial clusters and its sub types. The findings will be discussed under respective sections. The scores of TDC are not considered for qualitative analysis as there were negligible articulatory errors in the participants. The data of children with CI is represented with respect to the years of CI use. The percentage of correct and error productions were calculated as mentioned in method section 3.4.3.2.3.

4.2.3.2.1. Initial Clusters.

Initial clusters were divided into clusters with fricatives (/sk-/, /st^{h-}/, /sp-/,/sl-/), laterals (/gɭ-/, /pɭ-/, /bɭ-/, /kɭ-/), trill/flap (/tṛ -/, /bṛ -/, /pṛ -/, /kṛ -/, /gr-/) and glides (/kj-/, /ʃv-/). Percentage of error patterns under each cluster type was computed for initial clusters are tabulated in Table 4.78.

Table 4.78

Percentage of Consonant Cluster Errors in Word-Initial Position in Children with 2-3 and 3-4 years of CI Experience

Cluster Type	Implant experience	Correct	CS	CR			CO
				C_1	C_2	Coal	
With fricatives	2-3 years	15.63	3.13	21.88	31.25	37.50	15.63
	3-4 years	43.33	6.67	25.00	8.33	16.67	0.00
With laterals	2-3 years	25.00	6.82	2.27	38.64	18.18	9.09
	3-4 years	35.00	16.67	3.33	25.00	15.00	3.33
With trills/flaps	2-3 years	21.21	6.06	0.00	45.45	24.24	3.03
	3-4 years	44.00	26.67	1.33	18.67	9.33	0.00
With glides	2-3 years	25.00	0.00	6.25	18.75	50.00	0.00
	3-4 years	56.67	0.00	6.67	13.33	23.33	0.00
Total	2-3 years	21.60	4.80	7.20	36.00	28.8	8.00
	3-4 years	43.11	15.11	8.89	16.89	14.67	0.89

Note. CS- cluster simplification, CR- cluster reduction, C_1- consonant 1, C_2- consonant 2, Coal- coalescence, CO- cluster omission

a. Clusters with Fricatives (/sk-/, /st^h-/, /sp-/, /sl-/)

This cluster type consisted of /s/ (C_1) - stop (C_2) combination. As observed from Table 4.78 overall accuracy of clusters with fricatives production increased from 15.63 to 43.33% with increase in implant experience and cluster reductions were the predominant error type. Children with lesser implant experience exhibited a tendency for coalescence (e.g. /cu:l/ for /sku:l/) followed by C_2 deletion (e.g. /salam/ for /st^{h}alam/) and C_1 deletion (e.g. /pu:n/ for /spu:n/), whereas in older participants C_1 deletions followed by coalescence and C_2 deletions were frequent. Both group of participants exhibited similar pattern of coalescence errors, fricative clusters were substituted with affricates (e.g. /cu:l/ for /sku:l/) and fricatives (e.g. /hu:l/ for /skul/). The next frequent error was cluster omission in younger group (15.63%) which was completely absent in older participants. Cluster simplifications increased from 3.13 to 6.67% with increase in implant experience.

b. Clusters with Laterals (/gɭ-/, /pɭ-/, /bɭ-/, /kɭ-/)

This type of clusters consists of stop (C_1) - lateral (C_2) combination. Accuracy of lateral clusters showed minimal improvement with increase in implant experience (25 to 35%). Similar to fricative clusters, cluster reductions were the most frequent type of error observed in this type of clusters. There was no difference in pattern of cluster reductions with increase in implant experience. C_2 deletions (/ga:ssə/for /gla:ssə/) followed by coalescence (/ve:də/ for /ble:də/) and C_1 deletions (/la:ssə/ for /gla:ssə/) were the pattern demonstrated by both groups of CI. An increase in cluster simplifications (6.82 to 16.67%) and reduction in cluster omissions (9.09 to 3.33%) was noted with increase in implant experience. From the pattern of cluster reductions, it could be noted that lateral /ɭ/ (C_2) was frequently deleted. Coalescence patterns revealed substitution of C_1 with another stop (/pe:də/ for /ble:də/) and C_2 which is a lateral with glide (/ve:də/ for /ble:də/). Among the stop-stop substitutions, majority of the errors were voicing confusions. In children with lesser CI experience, cluster simplifications were observed only for cluster /gɭ/, whereas in children with longer implant use, it was observed for /pɭ/, /gɭ/ and /bɭ/ as well. This could be considered as a shift towards more developmentally appropriate stage from cluster reductions and omissions.

c. Clusters with Trills/Flaps (/tṛ-/, /bṛ-/, /pṛ-/, /kṛ-/, /gr-/)

This type of clusters consists of stop (C_1) – trill/flap (C_2) combination. Accuracy of trill clusters showed improvement with increase in implant experience (21.21 to 44%). Cluster reductions were the most frequent type of error observed in both groups. Similar to lateral clusters, no difference in pattern of cluster reduction was noted with increase in implant experience. i.e, C_2 deletions (/ʈe:n/ for /ʈre:n/) were followed by coalescence (/peʂə/ for /braʂə/). Coalescence patterns revealed substitution of C_1 with another stop

(/peʂə/ for /braʂə/) and C_2 with glide (/ja:mam/ for /gra:mam/). C_1 deletions were absent in both subgroups of CI. Cluster omissions were observed in minimal percentage (3%) in younger group and was absent in older group. A remarkable increase in the percentage of cluster simplification (6.06 to 26.67%) was observed with increase in CI experience. In children with less implant experience, cluster simplifications were observed only for cluster /tṛ-/ and /bṛ-/, whereas in children with longer implant use, it was observed for all other clusters investigated. Younger children had a tendency to delete one element of consonant cluster (cluster reductions). With increased CI experience, tendency to retain both elements of the cluster (cluster simplifications) was noted.

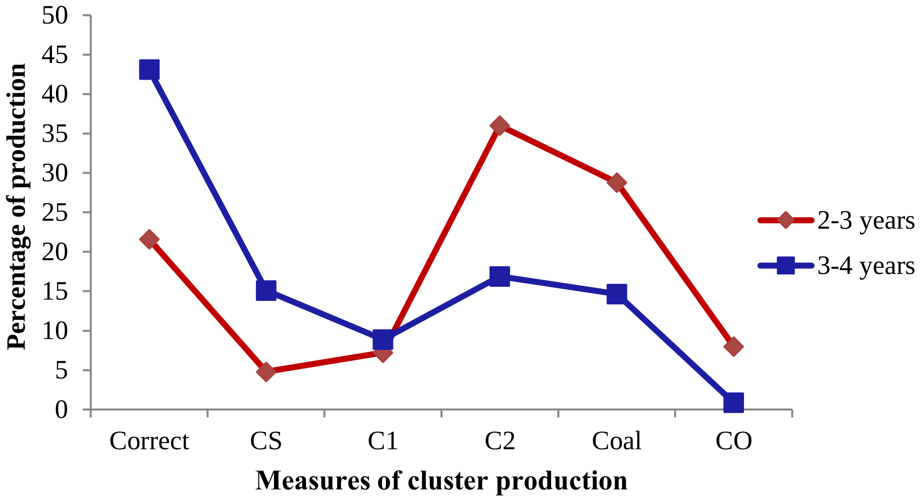
d. Clusters with Glides (/kj-/, /ʃv-/)

This cluster type consists of stop/fricative (C_1) - glide (C_2) combination. Correct productions of glide clusters showed considerable improvement with increase in implant experience (25% to 56.67%). Unlike other cluster types, cluster reductions were the only error observed in both group of participants. The pattern of cluster reduction was observed to be similar in both groups of children using CI. Interestingly, coalescence error (/ca:maṛa/ for /kja:maṛa/) constituted the major percentage of cluster reductions followed by C_2 deletions (/ka:maṛa/ for /kja:maṛa/, /ʃaasam/ for /ʃvasam/).

Cluster reduction was the predominant type of error in initial clusters for both groups of children using CI. Overall it could be evidenced that cluster simplification which is considered as a more developmentally advanced error increased significantly with increase in implant use for initial clusters. Also it was interesting to note that cluster reduction, which is a much earlier stage of cluster acquisition, notably reduced with CI experience. In other words, with increase in implant experience, children replaced developmentally earlier occurring errors with more developmentally appropriate errors indicating a shift towards normal acquisition of clusters. Overall error patterns of initial clusters in both subgroups of CI are depicted in Figure 4.59.

Figure 4.59

Mean Percentage of Word-Initial Cluster Production in Children with 2-3 and 3-4 years of CI Experience



Note. CS-cluster simplification, C_1-C_1 deletion, C_2-C_2 deletion, Coal-Coalescence, CO-cluster omission

4.2.3.2.2. Medial Clusters.

Medial clusters were also classified into clusters with fricatives (/-sk/, /-st/,/-stṛ/), laterals (/-lj/, /-dj/), trills/flaps (/-tṛ/, /-kṛ/), nasals (/-nr̠/, /-nt/, /-nɟ/, /-ɳɖ/, /-ŋg/, /-ndr/, /-ndj/) and /ʂ/ cluster (/-kʂ/). The findings will be discussed under each cluster type. Percentage of error patterns under each cluster type was computed for medial clusters are tabulated in Table 4.79.

Table 4.79

Percentage of Consonant Cluster Errors in Word-Medial Position in Children with 2-3 and 3-4 years of CI Experience

Cluster type	Implant experience	Correct	CS	CR				CO
				C1	C2	C3	Coal	
With fricatives	2-3 years	27.27	0.00	27.27	31.82	18.18	18.18	0.00
	3-4 years	37.78	6.67	24.44	4.44	17.78	13.33	0.00
With glides	2-3 years	16.00	28.00	44.00	0.00	-	12.00	0.00
	3-4 years	40.00	30.00	23.33	3.33	-	3.33	0.00
With trills/flaps	2-3 years	57.14	14.29	0.00	14.29	-	14.29	0.00
	3-4 years	66.67	26.67	0.00	6.67	-	0.00	0.00
With nasals	2-3 years	35.71	41.67	2.38	14.29	3.57	1.19	1.19
	3-4 years	65.71	23.81	0.95	3.81	4.76	0.95	0.00
/ʂ/ cluster	2-3 years	-	-	-	-	-	-	-
	3-4 years	0.00	6.67	53.33	6.67	-	33.33	0.00
Total	2-3 years	31.88	31.16	13.77	14.49	5.07	6.52	0.72
	3-4 years	52.44	16.89	12.00	4.44	5.78	5.78	0.00

Note. CS- cluster simplification, CR- cluster reduction, C_1- consonant 1, C_2- consonant 2, C_3- consonant 3, Coal - coalescence, CO- cluster omission

a. Cluster with Fricatives (/-sk/, /-st/,/-stṛ/)

This cluster type consists of fricative (C_1) - stop (C_2) and fricative (C_1) - stop (C_2) - trill (C_3) combinations. Minimal improvement with increase in implant experience (27.27 to 37.78%) was noticed. Cluster reduction errors constituted the major percentage errors in both subgroups. Children with lesser implant experience exhibited a tendency for C_2 deletions (e.g. /pusakam/ for /pustakam/) followed by C_1 deletions (e.g. /bikeṟə/ for /biskeṟə/). C_3 deletions (e.g. /vastam/ for /vastṛam/) and coalescence errors (e.g. /pucakam/ for /pustakam/) were exhibited in equal percentage ($C_2 > C_1 > C_3$=Coalescence). However, with increase in CI experience the pattern changed to higher C1 deletions followed by C_3 deletions, coalescence and C_2 deletions ($C_1 > C_3 >$ Coalescence$>C_2$). Cluster omissions were absent in both groups. Marginal increase in cluster simplifications (0% to 6.67%), a progressive stage of cluster acquisition was also observed with increase in implant experience. Cluster simplifications which was predominant in older group of participants comprised of retaining C_1 (fricative) and substituting C_2 (stop) with another stop (e.g. /bistet/ for /bisket/). Coalescence errors exhibited by both groups of participants were similar, where C_2 (stop) is omitted and C_1 is substituted with a palatal fricative (/ʃ/) or affricate (/c/) (e.g. /pucakam/ for /pustakam/).

b. Clusters with Glides (/-lj/, /-dj/)

This cluster type consists of lateral (C_1) - glide (C_2) and stop (C_1) – glide (C_2) combinations. With increase in implant experience, a notable increase in correct productions of glide clusters was achieved (16 to 40%). In children with lesser implant experience, cluster reductions were the predominant error type whereas for those with longer implant experience, cluster simplifications were predominant. Percentage of cluster simplification errors in younger group (28%) was comparable to that of older group (30%). C_1 deletion (e.g. /kajja:ɳam/ for /kalja:ɳam/) was the most frequent type of cluster reduction in both groups of children. Younger group had a notable percentage of coalescence errors as well (12%) but in older group both coalescence and C_2 deletions were negligible. Cluster omissions were absent in both groups of participants. In cluster simplifications C_2 (glide) was retained and C_1 (stop/lateral) was substituted with an affricate or stop.

c. Clusters with Trills (/-tṛ/, /-kṛ/)

This cluster type consists of stop (C_1) – trill (C_2) combinations. Unlike other cluster types, trill clusters demonstrated high accuracy of production even in younger group of participants (57.14%). Older group had an accuracy of 66.67% for this cluster type. Cluster reductions constituted the major error type in younger group of participants, whereas it was cluster simplifications in older group of participants. C_2 deletions and coalescence contributed equally to cluster reductions, whereas C_1 deletions were completely absent in younger group. Cluster omissions were absent in both groups of participants. In cluster simplifications, C_1 was retained and C_2 (trill) was substituted with lateral (e.g. /caklam/ for /cakṛam/).

d. Clusters with Nasals (/-nṟ/, /-nt/, /-ɳɖ/, /-ŋg/, /-nɟ/, /-ndr/, /-ndj/)

This cluster type consists of nasal (C_1) – stop (C_2), nasal (C_1) – affricate (C_2) and nasal (C_1) – stop (C_2) – flap/glide (C_3) combinations. A remarkable increase in correct production was noted with increase in implant experience (35.71 to 65.71%). Interestingly cluster simplifications which are considered as the most advanced error type, was the predominant error in both group of participants and cluster omissions were negligible. Younger group of participants had small proportion of cluster reductions in which C_2 deletions (14.29%) and C_3 deletions (3.57%) were frequent. Among the cluster simplification errors, C_1 (nasal) was retained and C_2 (stop) was substituted with other stops.

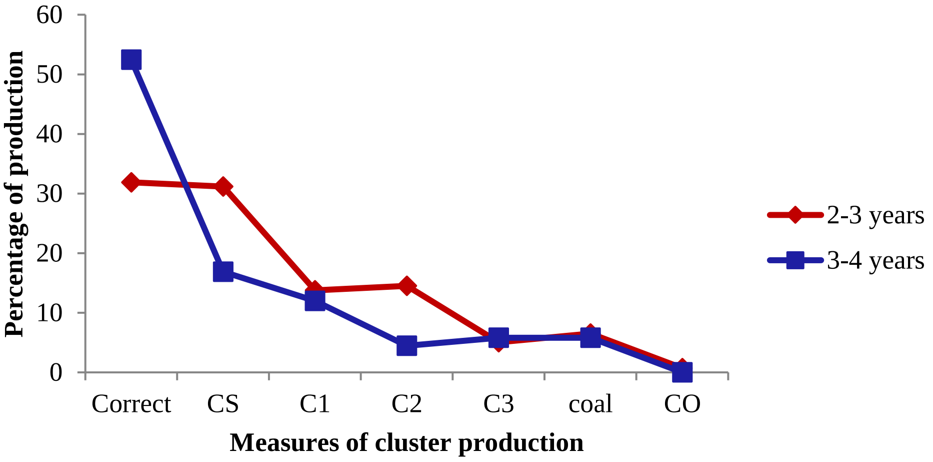
e. /-ʂ/ Cluster

This cluster type consists of stop (C_1) – fricative (C_2) combination. As the age of acquisition of this cluster type was above 6 years, it was not tested for younger group of participants. Compared to other cluster types /ʂ/ cluster was the most difficult cluster among clusters with an accuracy of 0%. Cluster reductions constituted the major error type in which C_1 deletions (53.33%) yielded the highest percentage followed by coalescence errors (33.33%). Cluster simplifications were observed in negligible percentage and cluster omissions were absent.

Overall for medial clusters, cluster reduction and cluster simplification was present in almost similar proportions. Cluster omissions were observed in minimal percentage in both younger and older group of participants. Overall error patterns of medial clusters in both subgroups of CI are depicted in Figure 4.60.

Figure 4.60

Mean Percentage of Word-Medial Cluster Production in Children with 2-3 and 3-4 years of CI Experience



Note. CS-cluster simplification, C_1-C_1 deletion, C_2-C_2 deletion, Coal-Coalescence, CO-cluster omission

To conclude, correct productions of clusters improved significantly with increase in implant experience. Medial clusters were produced with higher accuracy compared to initial clusters in both younger and older groups of children using CI. Also percentage of cluster simplifications was higher in medial clusters indicating a developmentally more appropriate error pattern than cluster reductions or omissions. Among initial clusters,

clusters with trills/glides had the highest accuracy for both younger and older group of participants and in medial position, it was clusters with nasals. Correct productions of clusters of all sub types of clusters in children using CI were significantly lower compared to TDC. Cluster reductions were the predominant error in both initial and medial clusters except clusters with nasals. Cluster omissions were the least common cluster error observed in both groups of participants. Children with longer implant experience had more cluster simplification errors compared to younger group.

4.4. Principal Component Analysis (PCA)

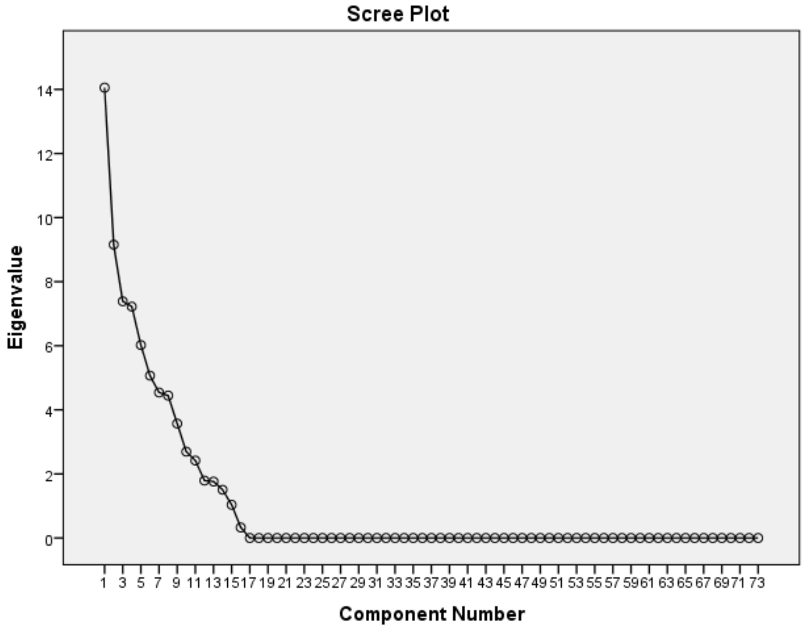
The present study investigated different acoustic parameters (temporal & spectral) of speech in children using CI and TDC. There were 9 temporal and 4 spectral parameters. Including the sub parameters there were 76 variables in acoustics making the data complex. Therefore an attempt was made to simplify and study inter-correlations of the data using principal component analysis (PCA).

The principal goal of PCA is to transform a large number of correlated variables into a smaller number of principal components for the ease of interpretation. Normality of the data was determined. Since the data followed non-normal distribution, non-parametric PCA along with Oblimin rotation was used. Spearman’s correlation was calculated for both group of participants (CI & TDC). However, correlations were not generated between many parameters for CI because of the missing values/ constant values. Out of 76 variables, three of them (VOT/d/, BD/d/ and CD/d/) consisted of 50% of constant/missing values and thus were not considered for analysis.

Non parametric PCA was carried out for both groups combined (CI & TDC) and for only TDC. PCA could not be done for CI group owing to the missing values. The number of components derived was determined by scree plot (Figure 4.61). A total of 37 components were generated and among them 11 had Eigen values greater than 1. Therefore, these 11 components were considered as most important for the present investigation. It should be noted that these parameters which are in the first component will have more loading/weightage or explain better variance compared to the parameters in the other components.

Figure 4.61

Scree Plot to Determine the Number of Components



In order to ensure the components that were identified accounted for the major part of variance, the percentage of cumulative variance was calculated as shown in Table 4.80. It can be noted that the 11 components identified accounted for 19.25%, 12.54%, 10.11%, 9.89%, 8.24%, 6.94%, 6.22%, 6.09%, 4.89%, 3.69%, 3.31% and had a cumulative variance of 91.19%.

Table 4.80

Percentage of Cumulative Variance Calculated for 11 Components

Component	Extraction Sums of Squared Loadings	
	% of Variance	Cumulative %
1	19.25	19.25
2	12.54	31.79
3	10.11	41.91
4	9.89	51.80
5	8.24	60.05
6	6.94	66.99
7	6.22	73.21
8	6.09	79.30
9	4.89	84.19
10	3.69	87.88
11	3.31	91.19

Details of the 11 components identified in the combined 4.0 to 7.11year children with CI and TDC are tabulated in Table 4.81. It can be noted that the communalities were greater than 0.5 for all the 11 components. Interestingly, the variables in the first component which obtained the highest loading were majorly temporal parameters. Most of the spectral parameters were aligned in the second component. The trend is not varying when analyzed separately for TDC alone and also when both groups were combined. It may be inferred that CI is also following a similar pattern of variance.

The variables in the first component which obtained the highest loading were majorly temporal parameters which contributed to 19.25% of variance. This consisted of measures in vowels (WD/o/, VD/i/), Stops (VOT/b/, VOT/p/, VOT/k/, BD/k/, CD/t/, CD/b/, CD/g/), Fricatives and affricates (FD/ʂ/, FD/s/, AD/c/, AD/ɟ/), nasals (NCD/m/, NCD/n̪/, NCD/ɲ/). Spectral measures were fundamental frequency, F_1/a/, and nasal murmur of /m/. The temporal variables included in the second component were majorly vowel duration (VD/a:/, VD/u/) and word duration (WD/u/,WD /a/, WD/i/, WD/i:/,WD/u:/) and spectral parameters included formant frequencies (F1 /u/, F_1/o/, F_2/u/) and nasal murmur (NM/n̪/). Few parameters of stops were also present (VOT/t/, VOT /ɖ/, BD /p/, CD /ɖ/,)

The third component consisted of measures of vowels (VD/a/, /u/ ratio), stops (VOT/g/, BD/g/, CD/ʈ/), Frication duration (FD/ʃ/) and formant frequency (F_1/a/, F_2/a/). The fourth component consisted of following variables like vowel duration of /e:/ & /i:/), word duration of /o:/, burst duration of /b/ , nasal consonant duration of /n/, /ɳ/, second formant frequency of /i/. The variables included in the fifth component were temporal measures (VD/o:/, VD/u:/, VD /o/, BD/ʈ /, CD/r̠/) except F2/o/. Similarly, the temporal variables included in the sixth component were CD/p/, BD/t/, NCD/ŋ/, and formant frequency of /i/. Seventh component includes only temporal measures. The eighth component consisted of the following variables WD/e/, BD /ɖ/, F1/i/. Ninth component comprised of /a/ ratio, tenth, VOT /ʈ/, eleventh CD/k/, and twelfth VSA.

Table 4.81

The Variables Distributed under 11 Components along with their Respective Communalities

	1	2	3	4	5	6	7	8	9	10	11	Communalities
WD/o/	0.83											1.00
AD /c/	0.80											0.99
FD/ʂ/	0.79											1.00
NCD/m/	0.78											1.00
CD/t/	0.77											1.00
CD/b/	0.74											1.00
FD/s/	-0.71											1.00
F1/e/	-0.70											1.00
WD/a:/	0.69											1.00
NM/ɲ/	-0.68											1.00
VOT/b/	0.67											0.97
VOT/p/	0.67											1.00
NCD/n̪/	0.66											1.00
NM/m/	-0.66											0.99
BD/k/	0.64											1.00
NCD/ɲ/	-0.62											1.00
CD/g/	0.61											0.98
AD /ɟ/	0.59											1.00
VD/i/	0.58											1.00
F_0	-0.55											1.00
VOT/k/	-0.41											0.93
VOT/t/		-0.73										1.00
VD/i:/		0.64										1.00
VOT/ɖ/		0.63										0.98
WD/a/		0.62										1.00
F1/o/		0.61										1.00
CD/ɖ/		0.61										1.00
WD/i/		0.60										1.00
/i/ ratio		0.59										1.00
F_1/u/		0.57										1.00
NM /n̪/		0.56										1.00
WD/u/		0.55										0.99

VD/a:/	0.55									0.99
VD/u/	-0.51									1.00
F_2/u/	0.49									1.00
WD/u:/	0.43									1.00
BD/p/	-0.43									1.00
VOT/g/		-0.83								1.00
F_2/a/		0.83								1.00
/u/ ratio		0.70								1.00
F_1/a/		0.65								1.00
FD /ʃ/		0.60								1.00
BD/g/		0.59								1.00
CD /ʈ/		-0.58								1.00
/o/ ratio		0.53								1.00
VD/a/		-0.51								1.00
VD/e:/			-0.64							1.00
NCD/n/			0.57							1.00
NCD /ɳ/			0.54							1.00
BD/b/			0.52							1.00
WD/o:/			0.47							1.00
VD/i:/			-0.46							1.00
F_2/i/			0.45							1.00
VD/o:/				0.74						1.00
WD/u:/				0.69						1.00
F_2/o/				-0.57						1.00
VD/o/				0.50						1.00
BD/ʈ/				0.48						1.00
CD/r̠/				-0.47						0.98
BD/t/					0.62					1.00
CD/p/					0.57					0.99
F_2/e/					-0.50					1.00
NCD/ ɲ/					-0.48					0.98
VD/e/						-0.64				1.00
/i/ ratio						0.52				1.00
WD/e:/						0.51				1.00
BD/ɖ/							0.63			0.99
F_1/i/							-0.62			1.00
WD/e/							0.48			1.00
/a/ ratio								0.63		1.00
VOT /ʈ/									-0.45	1.00

CD/k/	0.55	0.99
VSA		0.97

Note: VD- vowel duration, WD-word duration, VOT-voice onset time, BD-burst duration, CD-closure duration, NCD-nasal consonant duration, FD- frication duration, AD- affrication duration, F0-fundamental frequency, F_1/F_2- first /second formant frequency, NM- nasal murmur, VSA-vowel space area

It can be noted that majority of the variables in the first component which had better variance were temporal measures. This finding is well correlated with the observations of acoustic analysis which indicated that temporal measures were more affected than spectral parameters in children using CI. Also both CI and TDC groups exhibited a general trend in the variables which where aligned in the components. Hence, PCA analysis also indicated temporal parameters to be more sensitive in understanding the deviant speech characteristics of children with hearing impairment. This suggests the need to focus more on correction of temporal aspects of speech during speech therapy intervention.

Chapter 5: Discussion

Aim of the present study was to investigate the acoustic and articulatory characteristics of Malayalam speaking children using cochlear implant and to compare with age matched typically developing children. The acoustic parameters were analyzed based on the spectrographic measurements of the speech samples collected from children using CI and TDC. Acoustic analysis involved extraction of both temporal and spectral parameters of speech. The articulatory analysis included both quantitative and qualitative analysis of vowels, consonants and consonant clusters. The findings of acoustic and articulatory sections will be discussed under separate sections.

5.1 Acoustic Analysis of Speech in Children using CI and TDC

The first objective of the study was to investigate the acoustic (temporal & spectral) characteristics of speech between age groups in children using CI and TDC. The second objective was to compare the acoustic characteristics of speech between children using CI and TDC. The temporal and spectral analysis of vowels, stops, nasals, fricatives and affricates was carried out. Both objectives will be discussed together under each phoneme category for ease of understanding.

5.1.1. Temporal Parameters

5.1.1.1. Vowels.

The first finding of the present study was that vowel duration decreased for most of the vowels with an increase in the duration of CI experience. Reduction in duration with increase in age was noted to be similar to TDC group of the study supported by other developmental studies in Kannada (Sreedevi, 2007) and Oriya (Venkat & Lakshmi, 2012).

Secondly, it was noted that irrespective of the duration of implant use (2-3 years & 3-4 years), children using CI exhibited significant lengthening of vowels compared to TDC. The findings of the present study are in agreement with the reports of several earlier studies; Malayalam (Deepthy & Sreedevi, 2018); Kannada (Anusha et al., 2010; Rohini & Premalatha, 2011; Srividya & Premalatha, 2016), Mandarin (Yang et al., 2015; Yang & Xu, 2017) and Greek (Binos et al., 2020).

Thirdly, ratio of duration of long and short vowels was higher in children using CI with a significant difference noted for vowel /a/. The duration of long vowels was twice that of short vowels in TDC, whereas it was approximately thrice in children using CI. Similar findings have been reported by Anusha et al. (2010); Deepthy and Sreedevi (2018). A significantly higher ratio of /a/ may be related to the openness of the oral cavity and ease of production in children with hearing impairment.

The current study also found that word duration in both groups of participants (CI and TDC) reduced with increase in age as reported in English (Chermak & Schneiderman, 1986; Kubaska & Keeting, 1981; Smith, 1992, 1994). Another important finding is that both subgroups of CI exhibited significantly longer word duration compared to TDC which is in line with previous studies in Kannada (Anusha et al., 2010; Rohini & Premalatha, 2011; Srividya & Premalatha, 2016) and English (Uchanski & Geers, 2003). It has also been reported that the duration of vowel segments in words account for a larger percentage of the word duration (Uchanski & Geers, 2003).

Durational deviances may be reflected both in prolongation of steady states or in the transitions/movements from one articulatory position to the next.

This overall lengthening of vowel segments could be attributed to various reasons. It is probably due to the adaptive strategies used by children using CI to maximize the tactile and proprioceptive channels in the absence of auditory feedback for rapid, smooth production of complex motoric sequences of speech (Higgins et al., 1999; Svirsky et al., 1992). Another possible explanation is that children using CI with less implant experience might rely more on vision, and vision does not operate in a time frame as rapid as audition. This could probably happen even due to the visual feedback provided by parents or caregivers during home training. Increased duration also suggests that children using CI may need more time to form the articulatory gestures and transit from one target to the other. One more possible ground is that children with HI compensate for the inability of producing a consonant by prolonging the vowel since vowels are much more easily produced. It could also be reasoned out that the speech model provided by parents or caregivers might be exaggerated to acquire a better production which could lead to prolongation of vowels. Increased duration is also generally viewed as a marker of a less mature movement generator (Smith, 1978; Smith & Goffman, 1998). Therefore, with further refinement in the articulatory mechanism, the durational aspects of speech of CI users are expected to approach normal values compared to TDC (Dawson et al., 1995; Deepthy & Sreedevi, 2018; Uchanski & Geers, 2003).

5.1.1.2. Stops.

The parameters analyzed under stops were VOT, burst duration and closure duration. Among temporal parameters of stops, VOT is the most widely investigated parameter in children using CI. There are a few important findings which emerged from the acoustic analysis of stops. Firstly, similar to TDC group, a general trend of decrease in VOT was observed with the advance in the duration of implant use for most of the phonemes. An age-dependent decrease in VOT was also reported in Kannada speaking TDC (Savithri, 1996). Also voiced stops had longer VOT than unvoiced stops in both groups as reported in English (Docherty, 1992; Lisker & Abramson, 1964, 1967), Malayalam (Deepthy & Sreedevi, 2019a) and Kannada (Savithri et al., 2001,Shukla, 1989;).

Secondly, VOT of few of the phonemes approached normal limits with increase in CI experience. A number of researches have implied that VOT durations in children using CI were closer to the normal hearing peers as observed in Malayalam (Deepthy & Sreedevi, 2019a), Hindi (Kant et al., 2012; Kishore et al., 2018), Kannada (Anusha et al., 2010), English (Bharadwaj & Graves, 2008; Uchanski & Geers, 2003), Turkish (Aksoy et al., 2017), French (Grandon et al., 2017), Malay (Umat et al., 2015). Significant improvement in VOT can be attained after two years of implant experience and intensive aural-oral rehabilitation (Deepthy & Sreedevi, 2019a; Kant et al., 2012).

Thirdly, VOT of few phonemes in children using CI exhibited a significant difference compared to TDC. Similar results were reported by Higgins et al. (2003) in English that during the first few years after implantation children had difficulty in controlling the onset of voicing for voiceless consonants. For example, a significantly shorter VOT for few unvoiced stops (dental /t/) in children with lesser CI experience was observed which is in line with other studies in English (Higgins et al., 2003); Croatian (Horga & Liker, 2006); Greek (Koupka et al., 2019). This may relate to ongoing developmental changes in children with lesser implant experience (Okalidou, 2010). A significantly longer VOT in CI was observed for few voiced stops (retroflex /ɖ/ and dental /d/) compared to TDC which is supported by Higgins et al. (2003) in English and (Scarbel et al., 2013) in French. The authors interpreted the findings to suggest exaggeration of the voicing feature in children using CI.

Fourth, burst duration decreased with increase in duration of CI experience. Interestingly, burst duration of most of the phonemes approached normal limits with increase in implant use. This is in agreement with Deepthy and Sreedevi (2019a), where the authors found near normal values for most of the stops except for velar /g/ in Malayalam. Also, burst duration of unvoiced stops is reported to be longer compared to voiced stops which is again in agreement with Deepthy and Sreedevi, (2019); Kent and Read, (2002). Fifth, burst duration increased as the place of articulation moved backwards for voiced stops, i.e, bilabials< alveolars< velars for both CI and TDC as reported in Malayalam (Deepthy & Sreedevi, 2019a), Kannada (Gopi Sankar & Pushpavathi, 2016) and English (Kent & Read, 2002) in TDC.

Sixth, closure duration was found to be significantly longer in children using CI for most of the phonemes irrespective of duration of CI use as reported by Horga and Liker (2006); Deepthy and Sreedevi (2019a). Closure duration did not decrease considerably with increase in CI experience. Even after 3-4 years of implant experience closure duration remained as one of the most affected (significantly longer) temporal parameter compared to TDC in the present study. This could be due to the difficulty in coordinating the respiratory and phonatory systems. The difficulty in coordination would have resulted in longer closure duration prior to the articulatory release. Hudgins and

Numbers (1942) reported that HI speakers fail to coordinate the complex activity of respiration, phonation, and articulation and the resultant errors in timing occur at the segmental and suprasegmental levels of speech production. Also, longer closure duration can be attributed to exaggerated laryngeal gestures used as a compensatory strategy to achieve normal speech production. Closure duration of velar /k/ was found to be shorter compared to /p/ and /t/ in both CI and TDC groups. This finding is in consonance with other researches in Kannada (TDC) (Gopi Sankar & Pushpavathi 2016) and Dutch (Kujipers, 1989). Closure duration of stops were found to be longer for unvoiced stops compared to voiced stops in both CI and TDC groups which is in line with investigations by Lisker (1957); Savithri (1996) in typical population.

5.1.1.3. Nasals.

An age-dependent reduction in nasal consonant duration (NCD) was observed in TDC. Similarly, NCD reduced considerably with increase in implant use for most of the nasal phonemes with significant reduction noted for alveolar /n/ and retroflex /ɳ/. This reduction in duration could be attributed to various reasons: Firstly, nasals are one of the early acquired sounds and are produced with greater accuracy from an early stage of speech production. Secondly, nasals are low frequency sounds which are easier for perception through a CI which results in better auditory feedback. Thirdly, the frequency of occurrence of nasal phonemes are relatively high in Malayalam (Sreedevi & Irfana, 2013), which provides greater opportunities to learn. In TDC, duration of nasal consonants reduced with increase in age which indicates maturation of overall speech production mechanism.

Although NCD reduced with CI experience, compared to TDC, children using CI exhibited significantly longer NCD for all the nasals except for alveolar /n/ and velar /ŋ/ as observed by Deepthy and Sreedevi (2019c) in Malayalam. The authors reported significantly longer NCD for bilabial /m/, palatal /ɲ/ and retroflex /ɳ/. The increased duration could also be due to the tactile cues provided by SLPs during intervention for better feedback. As nasals are easier to produce, children would exaggerate the production also to perceive enhanced auditory feedback

5.1.1.4. Fricatives and Affricates.

Few important findings were derived from this section. First, frication and affrication duration reduced with age in TDC. Production of fricatives and affricates are generally described as difficult for children using CI because of high spectral energy of these phonemes. Interestingly, both frication and affrication duration decreased with increase in duration of CI use as reported by Fox and Nissen (2005); Nissen and Fox (2005) in English. The authors found that frication duration in adults were shorter compared to children.

Second, in children with lesser CI experience, frication duration of palatal /ʃ/ was comparable to that of TDC. This specific improvement in /ʃ/ could be due to low spectral energy concentration of this phoneme, which resulted in better auditory feedback compared to alveolar /s/. This can be evidenced from studies on perceptual confusion studies of /s/-/ʃ/ in Croatian (Liker et al., 2007) and German (Neumeyer et al., 2015).

Third, affrication duration of unvoiced affricate /c/ reached normal limits in children with lesser CI experience. However, voiced affricate /ɟ/ showed significantly longer duration compared to TDC. This is in line with studies in Cantonese (Hui & Hui, 2012) and Croatian (Horga et al., 2002; Mildner & Liker, 2003) Lengthening of duration for /ɟ/ could be explained by a "speed-and-accuracy" tradeoff, as the production of affricate requires higher degree of coordination for airstream projection. Increased time is necessary for children using CI to perform the articulatory gestures that are involved in the production of this complex consonant (Hui & Hui, 2012).

Fourth, fricatives and affricates are reported to be late acquiring and difficult to produce in children using CI. However, frication and affrication duration in children with longer CI experience exhibited comparable values to that of TDC. This could be attributed to the production characteristics of these sounds. Fricatives and affricates generally have a smooth production in English. However, in Indian languages, these sounds are produced with much more pressure release. Also, these are phonemes that are more sensitive to tactile cues compared to other class of phonemes. This would have helped children with CI to receive better tactile feedback during intervention which further improved their production accuracy. Yang et al. (2017) reported no significant difference in frication duration between children using CI and TDC.

5.1.2. Spectral Parameters

5.1.2.1. Fundamental Frequency (F_0).

Fundamental frequency of /a/ in children using CI was comparable to that of TDC in both age groups. Pitch control in children using CI was found to be improving with increase in duration of CI use. Fundamental frequency of /a/ decreased with increase in duration of implant use as supported by various studies (Higgins et al., 2003; Seifert et al., 2002; Wang et al., 2017). This finding suggests that children approximated the normal range of F_0 within 2-3 years post cochlear implantation which is in consonance with studies in Hindi (Joy et al., 2017), Chinese (Wang et al., 2017), English (Poissant et al., 2006), Slovene (Hocevar- Boltezar et al., 2006). As auditory feedback is habituated within a few years after implantation, the neuromuscular control of phonation gradually matures. Subsequently, they will be able to coordinate the movements of vocal folds, reduce the tension of vocal cords, lower their intonation, and gradually stabilize phonation. Leder et al. (1986) noted that F0 was one of the earliest voice parameters to approximate normal range after cochlear implantation. However, few other researchers have reported a significantly lower mean F_0 in CI group (Seifert et al., 2002; Srividya et al., 2016).

5.1.2.2. Formant Frequency (F_1 & F_2).

The formant frequencies F_1 and F_2 decreased towards normal values with increase in implant use for most of the vowels studied. The only exception of this trend was the F_1 of mid back vowel /o/ and F_2 of high front vowel /i/, which increased with implant use, though non-significant compared to TDC. Similarly, a general trend of decrease in both first and second formant frequencies with increase in age was observed in TDC as well. Concerning the relationship between physical changes and speech development, it has been found that as the length of the vocal tract increases during development, formant frequency decreases (Fant, 1960; Fitch & Giedd, 1999). The pattern of formant frequencies was uniform in CI and TDC groups irrespective of age. As documented in the previous literature, the change in formant frequencies was as follows: F_1- /i/ < /u/ < /e/ < /o/ < /a/ and F_2- /u/ < /o/ < /a/ < /e/ < /i/ (Eguchi & Hirsh, 1969).

The results of the present study indicated that formant frequencies of all vowels were comparable to that of TDC except for F_2 of /a/. This is in consonance with previous researches in Hindi (Kant et al., 2012), English (Uchanski & Geers, 2003), Croatian (Horga & Liker, 2006). Based on the fact that the formants of children with CI in the present study are in proximity to the typical values, it can be concluded that cochlear implantation has positively contributed to correct tongue placement in children with CI. Also, the intelligibility of vowels did not differ perceptually and this may be accounted for the statistically insignificant finding.

Though non-significant, formant values of CI group were higher compared to TDC which is supported by Jafari et al. (2016); Rohini and Premalatha (2011); Srividya and Premalatha (2016). The higher F_1 values observed in the present study could be probably due to greater reliance on jaw height changes in children using CI than TDC. This difference seems to be more related to the exaggerated visual feedback provided by parents or clinician during pre-implantation and to an extent post implantation as well. A significantly higher F2 /a/ observed in the present study is in agreement with Jafari et al. (2016). Baudonck et al. (2011) observed higher F_2 values of vowel /a/ in children using CI, but this difference was not statistically significant. However, a considerable reduction in F_2 /a/ was noticed in the older group of CI indicating improvements in tongue placement with increase in implant experience.

Overall, it can be noted that the second formant to be more affected in children using CI. This may be due to the fact that F_2 relies heavily on tongue placement and has less visibility compared to F_1, which is mostly controlled by jaw opening and tongue height that has high visibility for individuals with hearing loss (McCaffrey & Sussman, 1994; Monsen, 1976; Nicolaidis & Sfakiannaki, 2007; Ozbic & Kogovsek, 2010).

5.1.2.3. Vowel Space Area (VSA).

Vowel space area (VSA) in children using CI was comparable to that of TDC which is in agreement with Baudonck et al. (2011); Deepthy and Sreedevi (2019b); Uchanski and Geers (2003). The small insignificant increase in F_1 and F_2 values would have resulted in marginally higher vowel space in children with CI compared to TDC. A similar finding had been reported by Baudonck et al. (2011) where the authors concluded that increase in vowel space could also be the result of exaggerated articulatory movements modeled by the speech therapist and caregivers to facilitate better articulatory skills. Also, for better proprioceptive feedback, children would have imitated the exaggerated movements. Moreover, the age of implantation of participants of the present study were before 3 years (early rehabilitated) and were undergoing intensive auditory verbal therapy. According to Baudonck et al. (2011) early and intensive articulation training can lead to exaggerated or over articulation in children with HI. Further VSA was observed to decrease with increase in age which is supported by Vorperian and Kent (2007).

5.1.2.4. Nasal Murmur.

In the present study nasal murmur of all nasal phonemes in children using CI were comparable to TDC. This is in consonance with the findings of Deepthy and Sreedevi (2019c). The tactile cues provided during intervention would have helped for improved feedback. Also, nasal murmur consists of energy in frequencies below 1 kHz, with significant energy at low frequencies. This would help in better perception of frequency information through CI and thus lead to near normal values.

Yet, another finding of the present study is that there was no significant difference between gender for the acoustic measures studied in children using CI and TDC. This is in consonance with various other developmental studies (Lee et al., 1999; Vorperian et al., 2009). It has also been reported that there is no difference in vocal tract length till the age of 11 years which results in no gender differences in acoustic measures (Fitch & Giedd, 1999). Another study by Vorperian et al. (2009) reported that majority of vocal tract structures showed large differences across gender only after the age of 12. Findings on frication duration of /s/ in TDC indicated no gender difference (Gopi Sankar & Pushpavathi, 2016; Fox & Nissen, 2005).

The current study also reported high variability in the acoustic measures in both CI and TDC group with a higher variability noted for children using CI. Variability in the speech of children has been widely reported (Green et al., 2002; Kent, 1976; Savithri, 1996; Smith, 1978, 1992; Smith & Zelaznik 2004; Thelen & Smith, 1994; Tingley & Allen 1975). The variability seen in the developing motor system is an indication of a system acquiring new patterns of behavior (Thelen & Smith, 1994). The findings of Kent (1976) suggests that the variability of speech motor control progressively diminishes until the age of 8-12 years, when adult-like stability is achieved reflecting an increasing precision of motor control over a five- to eight- years’ (Kent 1976, Tingley & Allen 1975). It was also noted that there was no steady gradual reduction in variability of acoustic measures with increase in age. Similar findings were reported by Green et al. (2002); Smith and Zelaznik (2004), where they concluded that the variability of speech motor performance shows an overall decreasing trend with age that is overlaid with some transient periods of elevated variability and this occurs at the transitional stages in development when task demands greatly exceed a child’s capability (Thelen & Smith, 1994).

Based on the above discussion, the ***first hypothesis*** which stated there is no significant difference in the acoustic (temporal & spectral) characteristics of speech across age groups (4.0-5.11 years & 6-7.11 years) in children using cochlear implants and typically developing children is partially accepted.

Similarly, the ***second hypotheses*** which stated there is no significant difference in the acoustic (temporal & spectral) characteristics of speech between children using cochlear implants and typically developing children is partially accepted.

5.2. Articulatory Analysis of Speech in Children using CI and TDC

The third objective of the present study was to investigate the articulatory characteristics across age groups in children using CI. The fourth objective was to compare the articulatory characteristics between children using CI and TDC. The findings of both objectives will be discussed together for ease of description. Articulatory analysis included both quantitative and qualitative analysis of vowels, consonants and consonant clusters and the results will be discussed under respective sections.

5.2.1. Vowels

Percentage of vowels correct (PVC) was calculated for all six vowels in initial, medial and final positions based on their occurrence in respective positions in the language. There are four important findings which emerged from the study. First, vowels exhibited high accuracy of production in both subgroups of CI. This can be explained with respect to the early acquisition of vowels. Vowels are reported to be accurate even in early words (Davis & MacNeilage, 1990; Paschall, 1983). Indian authors have also reported early acquisition of vowels in languages like Malayalam (Divya, 2010; Maya & Savithri, 1990; Neenu & Sreedevi, 2011; Vipina & Sreedevi, 2011; Vrinda & Sreedevi, 2011), Kannada (Sridevi, 1976; Prathima & Sreedevi, 2009), Tamil (Thirumalai, 1972; Usha, 1986). Vowels are reported to be more accurately produced when compared to consonants. Also, vowels are more intense and are of longer duration than consonants, and also vowels are more easily perceived with the residual hearing present and can be cued by comparatively simpler and slower changes of acoustic patterns. Further, it has also been evidenced that vowels are among the first phonemes to be acquired after cochlear implantation (Ertmer, 2001; Serry & Blamey, 1999).

Second, mid-central vowel /ə/ and low-central vowel /a/ showed the highest accuracy and back vowels /u/ and /o/ were the most errored in both subgroups of CI. Better and increased productions of front and central vowels than back vowels are reported in the earlier literature (Blamey et al., 2001; Chin & Pisoni, 2000; Davis & MacNeilage, 1990; Ertmer, 2001; McCaffrey et al., 1999; Warner-Czyz & Davis, 2008).

Third, vowel production significantly improved with increase in CI experience. This finding is very well supported by various studies, in which significant improvement in overall production accuracy of both vowels and consonants are reported within a year of device use (Warner-Czyz & Davis, 2008; Warner-Czyz et al., 2010). Ertmer (2002) found an increase in the diversity of vowels and diphthongs within the first year of CI use. In contrast to this finding, Ertmer and Goffman (2011) reported moderately lower vowel accuracy scores (79%–83%) even after 2 years of CI experience indicating a not fully stabilized or immature vowel production system.

Fourth, from the analysis of vowel errors, it was noticed that substitution errors constituted the major percentage of errors and vowel omissions noted were minimal. This is in consonance with Paschall (1983), where the author reported the prevalence of vowel substitutions six times more than omissions in the early stages of speech acquisition in TDC. The author also reported that after 2-3 years of CI experience, there was a shift from vowel omissions to substitutions. Overall reduction in substitutions and variability of errors were noticed with increase in implant experience. Substitution with mid-central vowel /ə/ was common in children with lesser implant experience. With an increase in implant experience, substitutions with more proximal vowels were observed. Davis and MacNeilage (1990) reported substitution of neutralized vowels or neighboring vowels in the vowel space, particularly those lower and more front than the target in children using CI. Tye-Murray and Kirk (1993) stated high occurrence of neutral vowel substitution in children who are implanted after 3 years of age.

5.2.2. Consonants

5.2.2.1. Quantitative Analysis.

Quantitative analysis of consonants was carried out using percentage of consonants correct- revised (PCC-R) with respect to places and manners of articulation.

There are many interesting points drawn from this section. The first finding is that the consonant accuracy was significantly poor in children using CI compared to TDC which is in line with previous researches (Gillis, 2017; Tobey et al., 2011; Tomblin et al., 2008; Warner-Czyz & Davis, 2008). Articulatory acquisition in children using CI is reported to be systematic, but slower than in TDC (Blamey, Barry, & Jacq, 2001; Serry & Blamey, 1999).

Second, consonant productions improved with increase in CI experience for all places and manners of articulation as supported by previous studies in English (Guo et al., 2013; Tomblin et al., 2008) and French (Bouchard & Normand, 2007). Diversity in consonant inventory is observed to expand from labials and nasals to coronal and dorsal place and fricative, stop and glide manners (Blamey et al., 2001; Chin & Pisoni, 2000; Ertmer & Mellon, 2001) post implantation.

The third important finding is that among places of articulation, bilabials had the highest PCC-R scores and retroflex had the lowest in both sub groups of CI. This is in consonance with Bauchard et al.(2007); Serry and Blamey (1999); Tye-Murray et al. (2011) where the authors reported high accuracy of production of labial sounds which are highly visible followed by labiodentals, alveolars, velar and palatals (Ertmer & Mellon, 2001). Most of the early emerging sounds have visible places of articulation and was easier to perceive and produce because of a combination of auditory and visual cues. As a result, these phonemes become consistently accurate soon after implantation.

Fourth, in manners of articulation, glides were the most correctly produced followed by nasals, laterals, and stops. Trill, flap, and approximant /ʐ/ were the least accurate in both sub groups of CI. The better productions of glides and nasals could be attributed to the early acquisition of these sounds. Stops, glides and nasals are reported to emerge in the babbling stage itself (Anjana & Sreedevi, 2008; Reeny & Sreedevi, 2017). It is well reported in literature that children using CI were typically most accurate for early developing sounds such as stops, nasals (Ertmer et al., 2012; Warner-Czyz et al., 2010). The reason for low scores of approximants would be associated with the late acquisition of these sounds. Also, trills are reported to be better produced in consonant clusters than in singletons (Bleile, 2015; Scott & Milisen, 1954).

Fifth, stops and nasals were better articulated in initial position and fricatives, affricates, and approximants in medial position. It is reported that initial consonants are produced with greater accuracy compared to medial and final positions (Ertmer et al., 2012). Production accuracy of initial CV syllables was reported to be around 43% within one year (Warner-Czyz et al., 2010) and 60% accuracy after 2 years of device experience (Ertmer & Goffman, 2011). This could also be attributed to relatively greater perceptual salience of initial consonants as evidenced from auditory perception studies (Redford & Diehl, 1999). The authors also indicated that initial consonants appeared to have relatively higher amplitude and acoustic distinctiveness than final consonants. Another reason could be that the word initials/onsets may also “activate lexical representations which facilitate word perception, thus diminishing listeners’ dependence on acoustic-phonetic processing of the remaining segment of words”. It could also be because word initials have more robust and redundant acoustic cues and are less prone to coarticulation (Gow et al., 1996).

Medial position facilitated the production of fricatives, affricates and approximants. Merin (2017) reported that affricates /c/ and /ɟ/ are well facilitated in word-medial position in Malayalam speaking children with HI. Another study by Amulya and Sreedevi (2018) found lateral /ɭ/ and affricate /c/ is facilitated in medial position and affricate /ɟ/ and fricative /s/ in initial and medial positions in Kannada. Curtis and Hardy (1959) reported that /r/ is produced more correctly in word-medial position in English.

5.2.2.2. Qualitative Analysis.

a. Errors of Place of Articulation: The results of this section reveal five important points. First, detailed analysis of substitution error patterns revealed that among bilabials, nasal /m/ was the most correctly produced and /b/, the most errored phoneme in both subgroups of CI. Warner-Czyz and Davis (2008) reported nasal consonants are likely to have greater accuracy than stops. Also, other bilabial phonemes (/p/ & /b/) had few voicing errors which reduced the accuracy. Bilabials were most frequently substituted with bilabials itself in both subgroups of CI. Substitutions with same place of articulation can be positively correlated with the improved auditory feedback provided by CI. This effect can also be noted in the reduction in variability of substitutions as CI experience of participants increased.

Second, among labiodentals (/v/ & /f/), majority of participants with lesser CI experience produced /v/ more correctly compared to /f/. The higher accuracy for /v/ can be correlated with the early acquisition of glides. Error productions of /f/ in younger children can be because of the difficulty in perception of this sound compared to /v/. However, the accuracy of both phonemes was similar in the older group of CI which signifies a considerable improvement with longer CI experience. It was also noted that labiodentals were most frequently substituted with bilabial stops irrespective of implant experience which can be related to better visibility of bilabial phonemes. Substitutions with more anterior and visible place of articulation are amply reported in the literature (Bauchard et al., 2007; Serry & Blamey, 1999; Tye-Murray et al., 2011).

Third, phonemes which are acquired early had more perfection compared to the later ones. For example, among dentals, /d/ was the most difficult phoneme in initial as well as in medial positions in both subgroups of children using CI. This could be related to the late acquisition (>5 years) of /d/ resulting in high error productions, even in children with 3-4 years of CI experience. Among alveolars, lateral /l/ showed the highest improvement in production and retroflex approximant /ʐ/ was the most difficult phoneme with minimal improvement in both subgroups of CI. Retroflex phonemes are acquired much later than bilabials, labiodentals as reported in Malayalam (Deepa & Savithri, 2010; Neenu et al., 2011).

Among retroflex phonemes, unvoiced stop /ʈ/ and lateral /ɭ/ had the highest accuracy, which could be related to easy production of stop and lateral manner of articulation. Difficulty in production of retroflex sounds are also reflected in the high variability of substitutions with different places of articulation.

Fourth, palatal affricate /c/ and glide /j/ were the most correctly produced phonemes in initial and medial positions by both subgroups of CI. The higher accuracy of these sounds is possibly due to the improved production of manner feature glide (/j/) and better speech perception of affricate /c/ compared to other consonants in palatal class of phonemes. However, palatal nasal /ɲ/ being one of the early acquired phonemes had the least accuracy in initial position. This could be because of the difficulty in producing this particular place feature. However, /ɲ/ was one of the most accurately produced sound (>70% accuracy) in medial position indicating a better facilitating context for this phoneme. Voiced affricate /ɟ/ was the most difficult phoneme in medial position in both subgroups of CI. Accuracy of /ɟ/ was not high in the initial position also. Incorrect production of affricate /ɟ/ could be related to the complexity in articulation and timing of affricates. Among affricate sound class itself, /c/ is reported to have higher accuracy than /ɟ/ as evidenced from the acoustic studies in children using CI (Horga et al., 2002; Mildner & Liker, 2008).

Fifth, among velars, unvoiced /k/ had the highest accuracy and voiced /g/ had the least accuracy in both subgroups of CI irrespective of phoneme position. The low accuracy of /g/ could be related to devoicing bias for the stops in children using CI (Baudonck et al., 2010; Rødvik et al., 2019; Tye-Murray et al., 2011). The authors also reported that children with CI exhibited confusions among unvoiced stops with different place of articulation and voiced stops were confused with both unvoiced stops and voiced stops.

b. Errors of Manner of Articulation: There are seven important findings which emerged from the study. First, among stops and nasals, bilabials /p/ and /m/ were the most correctly produced by majority of the participants irrespective of the phoneme position and implant experience. The anterior place of articulation along with easier manner of articulation would have resulted in better accuracy of these sounds. Majority of the substitutions of nasals and stops were also with early acquiring anterior sounds.

Second, among fricatives, labiodental fricative /f/ and palatal /ʃ/ were the most correctly produced phonemes in initial and medial positions respectively, whereas palatal /s/ and /ʂ/ were the most difficult fricatives irrespective of implant experience. It is widely reported in speech perception studies that perception of /f/ and /ʃ/ are easy, compared to other fricatives (Giezen et al., 2010; Todd et al., 2011). Transcription analyses have shown that children with CIs are typically more accurate on target /ʃ/ than target /s/ (Blamey et al. 2001; Giezen et al., 2010; Reidy et al., 2017; Serry & Blamey, 1999). CIs deliver poorer frequency resolution for the higher frequencies. Therefore, children with CIs may have attempted to produce /s/ at lower frequencies resulting in the production of /ʃ/.

Third, in affricates, unvoiced /c/ was consistently the more correctly produced whereas, voiced palatal affricate /ɟ/ exhibited the least accuracy in all phoneme positions. Accurate production of unvoiced /c/ is reported in children using CI (Horga et al., 2002; Mildner & Liker, 2008). Lower accuracy of voiced /ɟ/ is attributed to the complexity of articulation and timing of affricates (Hui & Hui, 2012; Horga et al., 2002; Liker et al., 2007; Mildner & Liker, 2003)

Fourth, fricatives were predominantly substituted by affricates followed by other fricatives and stops. Substitutions of fricatives with other fricatives (Baudonck et al., 2010; Dillon et al., 2004, Faes & Gillis, 2016) and stops (Baudonck et al., 2010; Faes & Gillis, 2016; Flipsen & Parker, 2008; Gaul-Bouchard et al., 2007) are reported in literature.

Fifth, the most common substitutions of affricates were with other affricate (/c/-/ɟ/), stops, glides, flap and fricatives. It was also noted that unvoiced affricate /c/ was the most common phoneme substituted for the other affricate /ɟ/. This can be considered more as voicing confusion which is widely reported in children using CI. Smith (1975) noted that affricates were never substituted by other consonants but tended to be substituted by one of their cognates. However, there are other studies that reported affricates were most frequently substituted with a fricative (Mildner & Liker, 2008).

Sixth, among approximants, glides were the most accurate class of phonemes followed by laterals, flap and trill. Palatal glide /j/ had the highest percentage of correct production irrespective of phoneme position and implant experience. The better accuracy of production of glides could be attributed to their early acquisition (Ertmer et al., 2012; Smith, 1975; Warner-Czyz et al., 2010).

In a nutshell, place of articulation errors predominated manner errors. This finding is supported by Jakobson's (1941) Structuralist model of phonological acquisition stating that during speech acquisition, children would first distinguish vowels from consonants followed by consonantal contrast nasal-oral (m/p) and then by grave-acute (labial-alveolar) or place variations (Bernthal & Bankson, 2004). This indicates place features which are later developed during speech acquisition is more complex than manner features, demonstrating a normal trend of speech acquisition in children with CI also.

c. Errors of Voicing: Errors of voicing were one of the most frequent types of consonant errors found in children using CI (Higgins et al., 2003; Ryalls et al., 2003;Tye-Murray et al., 1995). The current study indicated more voicing errors for voiced phonemes for both stops and affricates indicating more devoicing errors. It was also noted that devoicing of voiced phonemes persisted even after 3-4 years of CI use, though there was considerable improvement seen in unvoiced phonemes. This devoicing bias in children using CI is abundantly reported in literature (Baudonck et al., 2010; Rødvik et al., 2019; Tye-Murray et al., 2011). Moreover, the complexity in achieving fine control of voicing makes it one of the late acquired features in speech acquisition (Ingram, 1999; Kent, 1992).

Rødvik et al. (2019) reported that this bias towards unvoiced stops was observed only in children using CI. The author postulates two reasons for this bias: 1. For voiced sounds, CI provides fundamental frequency feature poorly due to missing temporal information in the electrical signal and too shallow electrode insertion depth to cover the whole cochlea which is supported by other studies (Caldwell et al., 2017; Svirsky et al., 2015). 2. VOT helps the perception of unvoiced stops much easier than the voiced stops due to the aspirated pause between the stop and the following vowel in a VCV context (Rødvik et al., 2019). Another relevant reasoning would be the higher frequency of occurrence of unvoiced consonants in Malayalam compared to voiced consonants (Sreedevi & Irfana, 2013).

Few other studies have reported contrasting findings. Dillon et al. (2004); Tobey et al. (1991) reported one year post-implantation, children produced more voiced plosives than their unvoiced cognates. The accuracy of production of voicing feature was slightly higher for voiced consonants. An equal percentage of deletion of both voiced and unvoiced consonants are also reported (Dillon et al., 2004). The present study also indicated that unvoiced affricate /c/ was the most common phoneme substituted for the other affricate /ɟ/ which can be considered as a voicing error.

In general, it was observed that there was a considerable reduction in the number of substitutions in the older group of participants (3-4 years of CI experience). As the implant experience of participants increased, substitutions with phonemes with the same place or manner of articulation increased and the variability in class of phonemes substituted reduced indicating more proximity to the target phoneme. These improvements can be attributed to superior auditory feedback received through consistent use of CI as well as systematic and intensive auditory training received by the participants.

5.2.3. Consonant Clusters

There are few interesting points derived from the analysis of consonant clusters. Firstly, quantitative analysis of consonant clusters revealed medial clusters were produced more correctly compared to initial clusters. Various investigators have reported the early emergence of medial clusters compared to initial clusters in different Indian languages such as Malayalam (Neenu & Sreedevi, 2011; Vipina & Sreedevi, 2011; Vrinda & Sreedevi, 2011) Kannada (Deepa & Savithri, 2010; Rupela & Manjula, 2006) and Telugu (Neethipriya & Manjula, 2011; Sneha & Sreedevi, 2012). The percentage of correct production of all subtypes of clusters in children using CI was significantly lower compared to TDC. This is in agreement with Faes and Gillis, (2017); Von Mentzer et al. (2015).

Secondly, the overall accuracy of clusters increased considerably with increase in CI experience which is in consonance with the findings of Chin and Finnegan (2000); Dabiri et al. (2019); Faes and Gillis (2017). Chin and Finnegan (2000) reported that CC productions in children with 5 or more years of CI experience were almost similar to TDC. Further, among initial clusters, trill and glide clusters had the highest accuracy for both younger and older group of participants and in medial position, it was nasal clusters. Scott and Milisen (1954) reported trills to be better produced in the context of a cluster than in singleton consonants.

Thirdly, the error patterns of consonant clusters observed in children using CI was similar to the normal cluster acquisition stages of clusters in TDC which is supported by previous studies (Fulcher et al., 2014; McLeod et al., 2001; Smit et al., 1990. Further, the substitution errors during cluster simplification (i.e, production of both consonants) were predictable or similar to the substitution patterns of those singleton consonants. All these observations support the finding hat production of clusters in children using CI were similar to that of TDC.

Another important finding is that cluster reduction was the predominant type of error in initial clusters for both groups of children using CI which is in consonance with other studies (Chin & Finnegan, 2000; Dabiri et al., 2019; Flipsen & Parker, 2008). It has also been reported that children with CI had cluster reduction errors for a longer period than their normal-hearing peers (Ben-David, 2001). Overall it could be evidenced that cluster simplification which is considered as a more developmentally advanced error increased significantly with increase in implant use for initial clusters. Also, it was interesting to note that cluster reduction, which is a much earlier stage of cluster acquisition, notably reduced with CI experience. As hearing experience increases, child's awareness of cluster structure improves, and thus the use of cluster simplification is preferred over cluster deletion (Dabiri et al., 2019; Faes & Gillis, 2017). In other words, with increase in implant experience, children replaced developmentally earlier occurring errors with more progressive errors indicating a shift towards normal acquisition of clusters.

The cluster reduction patterns of children using CI exhibited an inclination towards the production of C_1 in all type of clusters (stop-lateral, stop trill/flap, stop/fricative (C_1) - glide (C_2) clusters), except for fricative-stop/liquid. This pattern of deletions can be explained based on sonority and markedness principle. According to sonority principle, the least sonorant member will be preserved. The order of sonority is as follows: stops>fricatives>nasals>liquids>glides. For example, if the target CC is /sp/ in /spu:ɳ/, children omit C_1 and produce it as /pu:ɳ/. According to markedness principle, the less marked consonant in the cluster is the one produced. For example, if /s/-plosive is the target cluster, then C_2 is produced (plosive), or /s/-nasal is the cluster, nasal is produced (C_1 is deleted).That is, the markedness scale of consonants are in the following order: stops, nasal, glide < fricatives, liquids, where a comma indicates no distinction.

Further, three element clusters (e.g. /-ndr-/, /-ndj-/) were present only in medial position. They were reduced to two elements (/-stṛ-/ to /tṛ/ or /st/) in majority of participants. However, a minimal percentage reduction to singleton consonants (majorly in children with lesser CI experience) was also observed (e.g. /-stṛ-/ to /t/). Similar findings were observed in young typically developing children (Divashree & Sreedevi, 2019; Sneha & Sreedevi, 2012).

The present study also indicated that the overall accuracy of medial clusters was higher than initial clusters, which is supported by Rupela and Manjula (2006) in Kannada. Unlike initial clusters (where cluster reductions were predominant) medial clusters exhibited almost equal proportions of cluster reductions and cluster simplifications. This increase in the percentage of cluster simplification (which is a more developmentally advanced stage of CC acquisition) is a good indicator of improvement in children using CI. It was also observed that with an increase in CI experience, the percentage of cluster reductions has reduced. Also, cluster omissions were observed in a very minimal percentage in both groups of participants.

To summarize, overall correct production of consonants in children with lesser CI experience was 46.18% and increased to 60.10% with longer CI use. Even though a few phoneme classes such as glides and nasals exhibited speech production accuracy of 70-80% in children having longer experience with CI, the overall accuracy of speech production was only 60.10% even in children with 3-4 years of CI experience. Unlike the findings of western studies which indicated high articulatory accuracy of speech in children using CI, the present study demonstrated relatively reduced intelligibility of speech. The lack of speech intelligibility as evident from the articulatory analysis of the present study was also reported by SLPs working with children using CI.

As part of ‘Shruthitharangam’ program in Kerala, in the first two years post implantation, children attend approximately 200 sessions of AVT training (weekly twice for 2 years) after which, most of them are mainstreamed into regular schools. On an informal interaction with SLPs who are part of this scheme, reported articulatory skills are worked upon for <25% during the first 2 years of AVT.

Parents of children with CI reported reduced intelligibility of speech, lack of availability of nearby speech therapy centers, lack of school support in providing additional speech therapy services. This further resulted in lack of dedicated time for articulation training. During the interaction with parents, it was informed that reduced articulatory skills and poor speech intelligibility are their major concerns. Anju (2017), in her unpublished study on Malayalam speaking school-going children with CI found that for 87% of children, teachers had to ask for repetition at least for a few utterances in order to understand the message conveyed by the CI using child in their classrooms. She further states that 12.9% of children's speech is accompanied with gestures in order to make others understand. Her data also revealed that only few (13%) of children with CI had nearly acquired the articulatory skills as that of typically developing peers. Thus the present study indicated that children using CI exhibited reduced speech intelligibility which highlights the importance of intensive articulation training from the early stages of speech intervention.

Based on the above discussion, the ***third hypothesis*** which stated there is no significant difference in the articulatory characteristics of speech across age groups in children using CI is partially accepted.

The ***fourth hypothesis*** which stated there is no significant difference in the articulatory characteristics of speech between children using CI and TDC is rejected.

Chapter 6: Summary and Conclusions

The present study investigated the acoustic and articulatory characteristics of Malayalam speaking children using cochlear implant in the age range of 4 to 8 years and a comparison with age matched typically developing children was made. A total of 80 participants were recruited for the study. The clinical group consisted of 30 children with congenital hearing loss fitted with CI before the age of 3 years. The participants of the clinical group were further divided into two subgroups based on the number of years of cochlear implant use. Subgroup I consisted of participants with 2-3 years of cochlear implant experience in the chronological age range of 4.0-5.11 years and subgroup II with 3-4 years of implant experience in the range of 6-7.11 years. TDC group was also divided into two subgroups of 25 participants each based on chronological age (4.0-5.11 & 6-7.11 years). of participants.

The study consisted of two major sections: 1. Acoustic analysis of speech 2. Articulatory analysis of speech. The test stimuli for acoustic analysis consisted of simple picturable words (10 VCV & 22 CVCV) and MAT-R was administered for detailed articulatory analysis. The speech samples were elicited through a picture-naming task and were audio-recorded. The acoustic measures considered for the study included nine temporal and four spectral parameters. Temporal measures were vowel duration, ratio of duration of long and short vowels, VOT, burst duration, closure duration, nasal consonant duration, frication duration, affrication duration and word duration. Spectral measures included fundamental frequency, formant frequencies (F_1 & F_2), Vowel space area and nasal murmur. For detailed articulatory profiling, vowels, consonants, and consonant clusters were analyzed quantitatively (PVC for vowels, PCC-R for consonants & PCCC for consonant clusters) and qualitatively (a confusion matrix for vowels, SODA and PMV analysis for consonants & percentages of cluster errors for consonant clusters).

Statistical comparisons were made between age groups of CI and TDC (4.0-5.11 years vs 6.0-7.11 years) and between children using CI and TDC. From the acoustic analysis, it was observed that there was a reduction in duration of most of the parameters analyzed with increase in age in children using CI and TDC. Among the acoustic parameters, substantial improvement was noted for spectral parameters. Most of the spectral measures approached typical values with 2-3 years of CI experience. However, temporal measures were significantly deviant from age-matched peers. Interestingly, fricatives and affricates the late acquiring sounds, approached normal limits in duration measures with 3-4 years of CI experience. However, vowel duration, closure duration, nasal consonant duration and word duration persisted to be significantly longer compared to TDC.

Articulatory analysis was carried out quantitatively and qualitatively for vowels, consonants and consonant clusters. Statistical comparisons were employed for quantitative measures of vowels, consonants and consonant clusters (PVC, PCC-R & PCCC). As there were negligible articulatory errors in TDC group, detailed qualitative analysis was carried out only for younger and older groups of CI.

Vowels

Vowel errors were less in children using CI compared to consonants and was found to decrease with increase in implant experience. Substitution errors constituted the major percentage of errors in medial position, whereas it was observed in small percentage in initial and final positions. Omission errors were fewer and addition errors were observed predominantly in initial position without compromising the target vowel. Substitution with mid-central vowel /ə/ was common in children with less implant experience, whereas such substitutions were absent in the older group. With increase in implant experience, substitutions with more proximal vowels were observed. Back vowels were the most difficult (/o/ & /u/) in both subgroups of CI.

Consonants

PCC-R scores increased with increase in implant experience for all places and manners of articulation. Significant improvement was noted only for bilabials and nasals. However, children using CI exhibited significantly lower scores for all places and manners of articulation compared to TDC. Qualitative analysis included SODA and Place, Manner and Voicing analysis (PMV) of all phonemes in initial, medial and final positions according to their occurrence in Malayalam.

Substitution errors constituted the predominant error type in consonants in both subgroups of CI. Considering the results pertaining to place of articulation, bilabials were the most correctly produced and retroflex by lowest percentage of participants in both sub groups of CI. The order of accuracy of different places of articulation was as follows: Retroflex < alveolar < dental < labiodental < palatals <velars<bilabials. Considering manner of articulation, glides were the most correctly produced class of phonemes by maximum percentage of participants and trill/flap/approximant /ʐ/ was the lowest in both sub groups of CI. The order of accuracy of different manner of articulation was as follows: /ʐ/< trill/flap < fricative <affricate<stops<laterals<nasals<glides.

Table 6.1 represents the phoneme classes with highest and lowest score and the phoneme position which facilitated improved production of these phonemes. It can be noted that stops and nasals were better produced in word-initial position and fricatives, affricates and approximants in word-medial position. Another important finding is that errors of place of articulation were higher compared manner errors. Voicing feature analysis revealed that devoicing errors were predominant in both subgroups of CI. Voiced aspirated phonemes demonstrated more devoicing errors compared to their unaspirated cognates. However, voicing errors reduced with increase in CI experience.

Table 6.1

Phoneme Classes with Highest and Lowest Score and the Phoneme Position which Facilitated better Production of these Phonemes

	Highest score	Lowest score
POA	Bilabials (/p/)	Retroflex (/z̢/)
MOA	Glides (/j/)	Approximants (/r/, /ṛ/, /z̢/)
	Phoneme position	
Facilitating context	Initial	Medial
	Stops and nasals	Fricatives, affricates and approximants

Consonant Clusters

Consonant clusters were analyzed in initial and medial positions. Most correctly produced cluster type in initial position was clusters with trills and glides. Predominant error type in initial position was cluster reduction. In medial position, clusters with nasals scored the highest. Interestingly cluster simplifications which are evident in the later stages of cluster acquisition constituted the major error type in medial position. In general, medial clusters were better produced than initial clusters. Overall it could be noted that children using CI performed significantly poorer compared to TDC. However, overall accuracy of production increased considerably for vowels, consonants and consonant clusters with increase in CI experience.

To summarize, findings of the present study provided a comprehensive acoustic and articulatory analysis of speech of children using CI in Malayalam. Detailed acoustic analysis indicated that temporal parameters were more affected compared to spectral measurements. This emphasizes the need for focusing more on the timing aspects of speech from the beginning of speech and language therapy. The study also attempted for a comprehensive profiling of articulatory errors and provides a detailed description of the most correctly/incorrectly produced phonemes with respect to place, manner and voicing feature. Summary of the most frequently substituted phonemes across phoneme positions is provided in Appendix F. Detailed analysis across phoneme positions (initial, medial, & final) helps in identifying facilitating context for correct production of phonemes which serves as guidelines for SLPs for framing articulation therapy goals.

The results of the present study highlight the need for remedial intense articulation training sessions along with AVT services for children with CI, especially in the early school-going age. A change in policies on services for providing continued support for children with CI during their schooling (e.g., enabling district or Panchayat wise/ remote access services) will surely benefit CI children to achieve more success at mainstream schools. In the recent times, with added focus on tele-therapy, the same holds more promise for children with CI for improving their speech intelligibility. Intensive counseling for parents on setting realistic expectations on the speech, language and academic performance of the child and also on effectively handling peer pressure at school is also considered to be the need of the hour.

Implications of the Study

- The outcomes of the present study contribute to the existing understanding of speech characteristics of Malayalam speaking children using CI
- The study indicated that temporal measures are significantly affected in children

using CI; hence have to be given more emphasis during intervention.

- Provides quantitative and qualitative articulatory error analysis of speech in Malayalam speaking children using CI
- Study provides detailed information on the most correctly/ incorrectly produced phoneme/ phoneme class, phoneme position which facilitates production of a particular class of phoneme. This would help SLPs to make appropriate intervention plans for articulation training to facilitate speech intelligibility in children using CI
- Helpful in re-mapping of cochlear implant depending on the phoneme class affected.
- Highlights the importance of focusing on speech intelligibility at early stages of speech intervention and the need for school/ district wise availability of speech therapy.

Limitations of the Study

- The number of words available for articulatory analysis was variable at different phoneme positions for calculating PCC-R. Including equal number of words would have helped in more uniformity of data.
- Intervention after 2 years of AVT was not controlled

Future Directions

- The present study can be replicated in other languages in order to obtain language-specific data on children using CI
- To investigate articulatory abilities at narration/ conversation level in children using CI
- To assess the articulatory abilities after intensive articulation training in children using CI
- Longitudinal studies on speech and language acquisition in children using CI
- To investigate the effect of facilitating phoneme position on speech sounds in children using CI

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Appendix A

ALL INDIA INSTITUE OF SPEECH AND HEARING

Information to the Participants

Title of doctoral thesis: Acoustic and articulatory characteristics of Malayalam speaking children using cochlear implant

Dear parent,

The present doctoral study aims at investigating the speech characteristics of Malayalam speaking children using cochlear implant. The study involves presentation of picturable words on a computer screen and the child has to name the picture. The responses will be audio recorded and analyzed later. The approximate time required for recording of the speech sample would be around two to three hours with short breaks in between. The participants involved in the study will encounter no risk during recording. I assure you that the collected information will be used for the purpose of the study only. I also clarify that there is no influence or pressure of any kind on your part to make your child participate in the study.

Informed Consent

I have been informed about and understand the purpose of the study and the need for my child’s participation in it. I also understand that the procedure is not harmful and has only research benefits. I understand that I have the right to refuse participation or withdraw my consent at any time during the procedure. I give my consent for my child’s participation in this study.

I, ____, the undersigned, give my consent for my child’s participation in this study.

(AGREE/DISAGREE)

Signature of Parent/Guardian Signature of Investigator

Name:

Address:

Appendix B

Target Word List for Acoustic Analysis in Malayalam

Sl. No.	*Word*	*IPA*
1.	അമ്മ	/amma/
2.	ആന	/a:na/
3.	ഇല	/ila/
4.	ഈച്ച	/i:cca/
5.	ഉള്ളി	/uɭɭi/
6.	ഊഞ്ഞാൽ	/u:ɲal/
7.	എലി	/eli/
8.	ഏണി	/e:ɳi/
9.	ഒന്ന്	/on̪n̪ə/
10.	ഓല	/o:la/
11.	പല്ല്	/pallə/
12.	ബസ്സ്	/bassə/
13.	തത്ത	/tatta/
14.	ടയർ	/ʈayaṛ/

15.	കാക്ക	/ka:kka/
16.	ഗദ	/gada/
17.	ചീപ്പ്	/ci:ppə/
18.	റബ്ബർ	/ṛabbar/
19.	മുട്ട	/muʈʈa/
20.	മുടി	/muɖi/
21.	ബാഗ്	/ba:gə/
22.	സോപ്പ്	/so:ppə/
23.	ശിവൻ	/ʃivan/
24.	ഷർട്ട്	/ʂaRʈʈə/
25.	ജീപ്പ്	/ɟi:ppə/
26.	മാങ്ങ	/ma:ŋa/
27.	മഞ്ഞ	/maɲɲa/
28.	നാല്	/ n̪a:lə/
29.	ഞണ്ട്	/ɲandə/
30.	ഡോക്ടർ	/ɖo:kʈaR
31.	ദോശ	/do:ʃa/
32.	പൂമ്പാറ്റ	/pu:mba:ṟa/

Appendix C

Picture Stimuli for Acoustic Analysis

1.അമ്മ

2. ആന

3. ഇല

4. ഈച്ച

5.ഉള്ളി

6.ഊഞ്ഞാൽ

7.ഏലി

8. ഏണി

9.ഒന്ന്

1

10.ഓല

11.പല്ല്

12.ബസ്സ്

13.തത്ത

14.ടയർ

15.കാക്ക

16.ഗദ

17. ചീപ്പ്

18.റബ്ബർ

19.മുട്ട

20.മുടി

21.ബാഗ്

22. സോപ്പ്

23.ശിവൻ

24.ഷർട്ട്

25. ജീപ്പ്

26. മാങ്ങ

27. മഞ്ഞ

🟨

28. നാല്

4

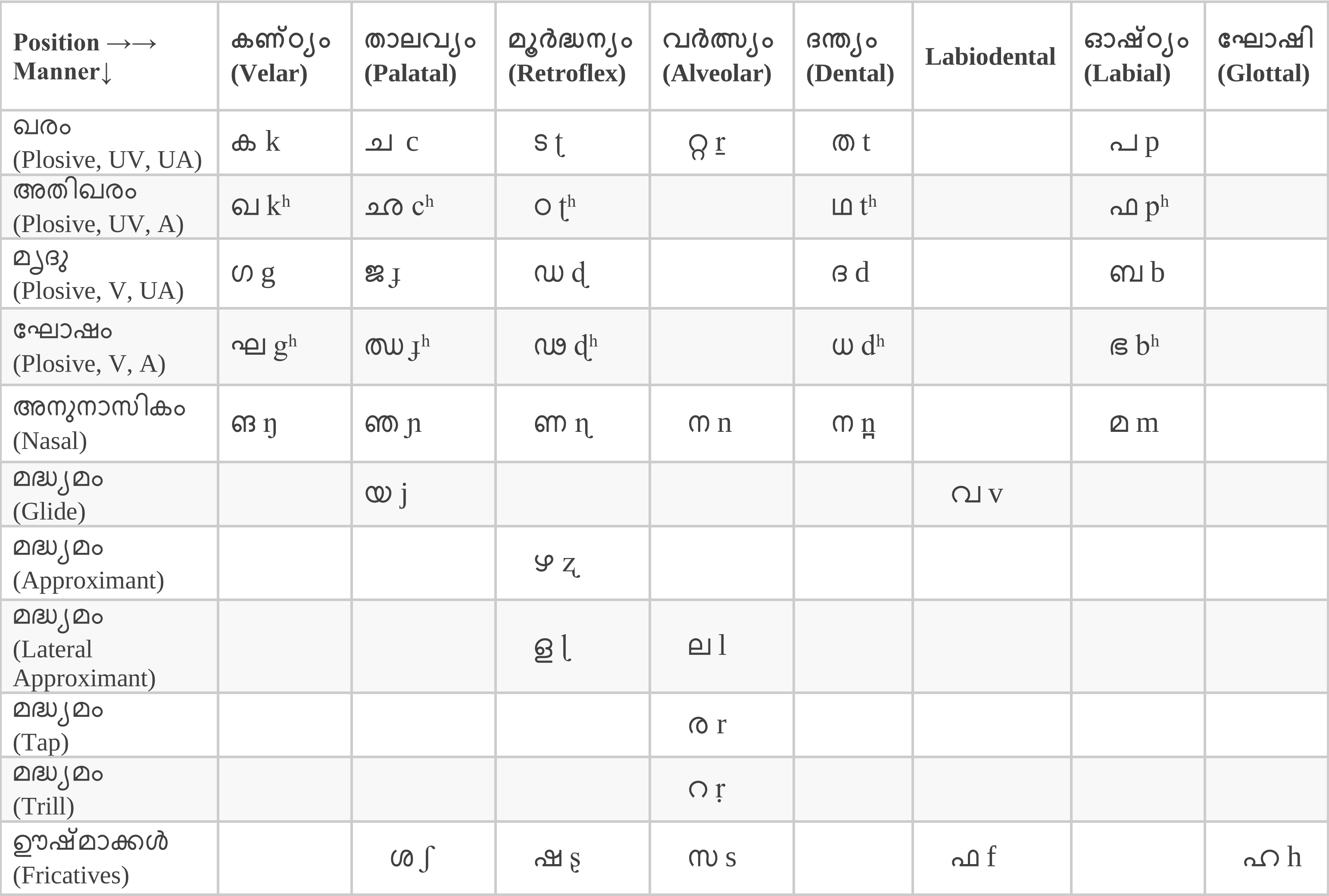
29. ഞണ്ട്

30. ഡോക്ടർ

31.**ദോശ** 32. പൂമ്പാറ്റ

Appendix D

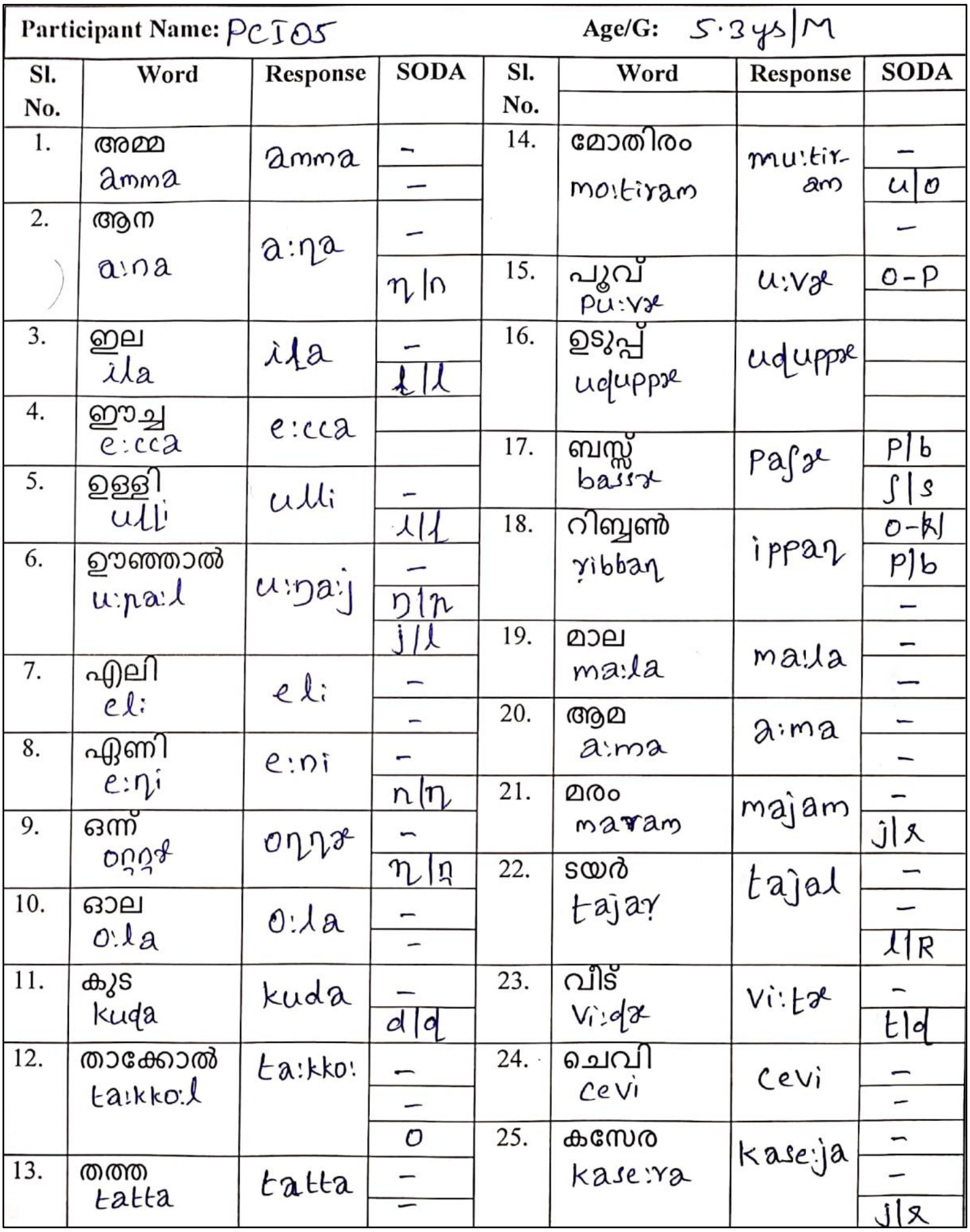
Screenshot of Malayalam IPA (Kavya Manohar, 2020)



Position →→ Manner↓	**കണ്ഠ്യം (Velar)**	**താലവ്യം (Palatal)**	**മൂർദ്ധന്യം (Retroflex)**	**വർത്സ്യം (Alveolar)**	**ദന്ത്യം (Dental)**	**Labiodental**	**ഓഷ്ഠ്യം (Labial)**	**ഘോഷി (Glottal)**
ഖരം (Plosive, UV, UA)	ക k	ച c	ട ʈ	റ്റ r̠	ത t		പ p	
അതിഖരം (Plosive, UV, A)	ഖ kʰ	ഛ cʰ	ഠ ʈʰ		ഥ tʰ		ഫ pʰ	
മൃദു (Plosive, V, UA)	ഗ g	ജ ɟ	ഡ ɖ		ദ d		ബ b	
ഘോഷം (Plosive, V, A)	ഘ gʰ	ഝ ɟʰ	ഢ ɖʰ		ധ dʰ		ഭ bʰ	
അനുനാസികം (Nasal)	ങ ŋ	ഞ ɲ	ണ ɳ	ന n	ന n̪		മ m	
മദ്ധ്യമം (Glide)		യ j				വ v		
മദ്ധ്യമം (Approximant)			ഴ ɻ					
മദ്ധ്യമം (Lateral Approximant)			ള ɭ	ല l				
മദ്ധ്യമം (Tap)				ര r				
മദ്ധ്യമം (Trill)				റ ṛ				
ഊഷ്മാക്കൾ (Fricatives)		ശ ʃ	ഷ ʂ	സ s		ഫ f		ഹ h

Appendix E

Sample of Filled Scoring Sheet of a Participant using CI



Participant Name: PCI05 Age/G: 5·3ys|M

Sl. No.	Word	Response	SODA	Sl. No.	Word	Response	SODA
1.	അമ്മ amma	amma	– –	14.	മോതിരം mo:tiram	mu:tir-am	– u|o –
2.	ആന a:na	a:ɳa	– ɳ|n	15.	പൂവ് pu:və	u:və	o-p
3.	ഇല ila	iɭa	– ɭ|l	16.	ഉടുപ്പ് uɖuppə	uɖuppə	
4.	ഈച്ച e:cca	e:cca		17.	ബസ്സ് bassə	paʃə	p|b ʃ|s
5.	ഉള്ളി uɭɭi	ulli	– l|ɭ	18.	റിബ്ബൺ ṛibbaɳ	ippaɳ	o-ṛ p|b –
6.	ഊഞ്ഞാൽ u:ɲa:l	u:ŋa:j	– ŋ|ɲ j|l	19.	മാല ma:la	ma:la	– –
7.	എലി eli	eli	– –	20.	ആമ a:ma	a:ma	– –
8.	ഏണി e:ɳi	e:ni	– n|ɳ	21.	മരം maram	majam	– j|r
9.	ഒന്ന് on̪n̪ə	oɳɳə	– ɳ|n̪	22.	ടയർ tajaṛ	tajal	– – l|R
10.	ഓല o:la	o:la	– –	23.	വീട് vi:ɖə	vi:tə	– t|ɖ
11.	കുട kuɖa	kuda	– d|ɖ	24.	ചെവി cevi	cevi	– –
12.	താക്കോൽ ta:kko:l	ta:kko:	– – o	25.	കസേര kase:ra	kase:ja	– – j|r
13.	തത്ത tatta	tatta	– –				

Appendix F

Target Phoneme with its Common Substitutions

Manner	Phoneme	Phoneme position	Commonly substituted phoneme
Stops	/p/	Initial	No substitution errors

Manner	Phoneme	Phoneme position	Commonly substituted phoneme
		Medial	/t/
	/b/	Initial	/p/, /m/
		Medial	/p/
	/bʰ/	Medial	/p/
	/t/	Initial	/ʈ/, /k/
		Medial	/j/, /ɖ/,
	/tʰ/	Medial	/k/
	/d/	Initial	/t/, /t/, /ʈ/, /ɖ/
		Medial	/j/, /ʈ/, /ɖ/
	/dʰ/	Medial	/t/, /d/
	/r̲/	Initial and medial	/c/, /t/
	/ʈ/	Initial	/t/
		Medial	/t/,/c/, /r̲/
	/ʈh/	Medial	/ʈ/, /r̲/
	/ɖ/	Initial	/ʈ/,/t/
		Medial	/ʈ/, /d/
	/k/	Initial	/g/, /t/
		Medial	/t/
	/kʰ/	Initial	/k/
		Medial	/k/, /g/
	/g/	Initial	/t/, /d/
		Medial	/k/,/t/
	/gʰ/	Medial	/h/
Nasals	/m/	Initial	/v/
	/n̪/	Initial	/n/
		Medial	/ɳ/
	/n/	Medial	/j/, /l/, /ɲ/
		Final	/j/, /l/
	/ɳ/	Medial	/j/
		Final	/n/
	/ɲ/	Initial	/j/,/c/
		Medial	/n/
	/ŋ/	Medial	/n̪/, /ɳ/
Fricatives	/f/	Initial	/p/
	/s/	Initial	/c/, /j/
		Medial	/ʃ/, /c/

Manner	Phoneme	Phoneme position	Commonly substituted phoneme
	/ʂ/	Initial and medial	/ʃ/, /c/
	/ʃ/	Initial and medial	/c/
Affricates	/c/	Initial Medial	/ɟ/, /ʃ/,/t/ /ʃ/
	/cʰ/	Medial	/c/
	/ɟ/	Medial	/j/,/t/, /d/
Glides	/j/	Initial Medial	/c/, /t/ /l/, /ʃ/
	/v/	Initial Medial	/p/, /b/ /b/
Laterals	/l/	Initial Medial Final	/j/, /ṛ/ /ɭ/,/j/ /j/, /r/
	/ɭ/	Medial Final	/j/, /l/ /l/
Trill	/ṛ/	Initial Medial Final	/j/, /r/ /ɭ/, /ɖ/ /ɭ/, /l/
Flap	/r/	Initial Medial	/c/, /j/ /j/, /d/
Approximant	/ʐ/	Medial	/j/