LOUDNESS PERCEPTION IN CHILDREN USING HEARING AIDS AND CHILDREN USING COCHLEAR IMPLANTS

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CERTIFICATE

This is to certify that the thesis entitled ***'Loudness perception in children using hearing aids and children using cochlear implants'*** submitted by Ms. Shubha Tak for the degree of Doctor of Philosophy in Audiology to the University of Mysore, Mysuru was carried out at the All India Institute of Speech and Hearing, Mysuru.

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DECLARATION

I declare that this thesis entitled ***'Loudness perception in children using hearing aids and children using cochlear implants'*** which is submitted herewith for the award of the degree of Doctor of Philosophy in Audiology to the University of Mysore, Mysuru is the result of work carried out by me at the All India Institute of Speech and Hearing, Mysuru, under the guidance of Prof. Asha Yathiraj, Former Professor of Audiology, 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.

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Abstract

The study compared two loudness perception measures (loudness growth identification & intensity discrimination) in children using a single cochlear implant (*n* = 25), children using binaural hearing aids (*n* = 20), and typically developing children (*n* = 31). In the children using hearing aids, the effect of compression parameters on loudness perception was also evaluated in three different conditions (own prescribed hearing aids, linear hearing aids, & non-linear hearing aids). While the participants' own hearing aids had lesser compression compared to the non-linear hearing aids, the linear hearing aids had no compression. The children aged 6 to 15 years, were evaluated using three warble-tones (500 Hz, 1000 Hz, & 4000 Hz) and three vowels (/u/, /a/, & /i/). Loudness growth was measured using a 'Loudness growth chart' having six loudness levels (very soft, soft, comfortable, loud, too loud, & very loud, & paining) and intensity discrimination was assessed using a Psycon software.

Only 48% of the children using cochlear implants and 65% of children using hearing aids could give consistent responses in the loudness growth identification test, while all typically developing children could do so. Further, on the loudness growth test, among the hearing aid users no significant difference occurred between the three hearing aid conditions for most stimuli. Across the three participant groups, significant differences were obtained mainly for the soft loudness levels for most stimuli. Both the clinical groups required more intensity to perceive the softer loudness levels compared to the normal hearing children. However, the children using cochlear implants did not differ significantly from the children using hearing aids for most loudness levels and stimuli.

The intensity discrimination thresholds across the three hearing aid conditions were significantly better when the children used the linear hearing aids than when they wore their

own prescribed hearing aids only for a few stimuli (500 Hz & 4000 Hz). On the other hand, between linear and non-linear hearing aids, the discrimination thresholds were significantly different for most stimuli (500 Hz, 1000 Hz, 4000 Hz, & /i/). Further, across the three participant groups, the typically developing children had significantly better discrimination thresholds than both the clinical groups for the majority of stimuli. However, no such difference was obtained between children using cochlear implants and children using hearing aids for most of the stimuli.

Thus, from the findings of the study it was observed that the warble-tones tended to differentiate the three participant groups better than did the vowels. This was observed for both loudness perception measures that were studied. Further, it was noted that loudness growth identification and loudness discrimination thresholds varied across the three participant groups as well as across the three hearing aid conditions. This was seen only for a few stimuli. Hence, it can be inferred that the devices worn by the two clinical groups did affect loudness growth perception at low levels, but did not do so for moderate to loud signals. Intensity discrimination was also adversely affected in the clinical groups wearing listening devices when compared to typically developing children. Based on the findings of the three hearing aid conditions, it is recommended to use lesser compression in listening devices to enable children with hearing impairment to perceive loudness cues akin to typically developing children.

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1. Introduction

Loudness, a subjective impression of the magnitude of a sound, has been demonstrated to be altered by sensory and cognitive abilities (Schneider, 1980; Steinberg & Munson, 1936). Besides subjective variables, loudness is also noted to vary depending on different physical parameters such as intensity, frequency, duration and bandwidth. Researchers have noted that loudness was a power function of intensity (Bartoshuk, 1964; Robinson & Gatehouse, 1996; Stevens, 1955). This implied that at higher levels the growth in loudness is more gradual and is steeper at lower levels. Further, Hellman and Zwislocki (1963) also noted that at levels near threshold the loudness growth was steeper than at the higher levels. Loudness was also found to be affected by the frequency of stimuli (Fletcher & Munson, 1933; Hellman, 1976; Hellman & Zwislocki, 1968; Takeshima et al., 2003). At lower frequencies the loudness growth was found to be much faster than at higher frequencies (Fletcher & Munson, 1933; Hellman & Zwislocki, 1968; Takeshima et al., 2003). With the increase in duration, loudness was also found to increase (Epstein & Florentine, 2005, 2006; Florentine, 1986; Florentine & Poulsen, 1996). It was also observed by Epstein and Florentine (2005) and Epstein and Florentine (2006) that temporal integration was maximum at moderate levels, compared to low and high levels. Further, it was also found that loudness was affected by bandwidth, such that as the frequency separation exceeded a critical band, loudness increased. However, for frequency separation less than one critical band, loudness was noted to be independent of bandwidth (Leibold et al., 2007; Zwicker et al., 1957).

In normal hearing individuals, loudness perception was noted to be essential for many day-to-day activities such as distance perception (Ashmead et al., 1990; Coleman, 1963; Strybel & Perrott, 1984), perception of emotions in speech (Fónagy, 1981; House, 1990; Laukkanen et al., 1996; Sauter et al., 2010; Whiteside, 1999), and stress (Bull et al., 1984; Eilers et al., 1984; Fry, 1955, 1958; Kumar & Bhat, 2009; Lieberman, 1960; Weber et al., 2004). Coleman (1963) observed that loudness played a major role in distance perception when visual cues were degraded due to physiological or environmental obstacles. However, Strybel and Perrott (1984) reported that when the signal was farther away, at a distance of 609 to 4876 cm, their subjects used loudness discrimination cues for distance judgment. On the other hand, at the shorter distances of 49 to 304 cm, the judgment degraded. Similarly, Zahorik (2002) and Guo et al. (2019) noted that perceptual weight on intensity for distance perception might vary depending on the source distance.

Researchers have also found intensity cues to be essential for emotional perception (Fónagy, 1981; House, 1990; Laukkanen et al., 1996; Sauter et al., 2010; Whiteside, 1999). House (1990) noted that besides frequency, intensity dynamics were also used by participants to categorize happy, sad and neutral moods. Whiteside (1999) reported that in the acoustical analysis of different emotions (such as neutral, cold anger, hot anger, happiness, sadness, interest, & elation), hot anger was associated with greatest energy and sadness was associated with diminished energy. Further, Fónagy (1981) found that anger led to spasmodic contraction of the vocal tract, resulting in a sudden outburst leading to an increase in loudness. Similarly, Laukkanen et al. (1996) and Sauter et al. (2010) also reported that enthusiasm and anger were associated with increased fundamental frequency as well as sound pressure level. Additionally, Sauter et al. (2010) noted that sadness was related to lower levels of intensity.

Loudness was noted to be important in the perception of stress. Fry (1955) and Fry (1958) found that both duration as well as intensity served as cues for stress perception. Likewise, Lieberman (1960) found that amplitude and fundamental frequency were relevant acoustic correlates of stress perception. However, the author concluded that individuals make judgment regarding stress pattern by combining cues such as amplitude, fundamental frequency, and duration. Intensity as a cue for the perception of stress has demonstrated in several other studies (Bull et al., 1984; Eilers et al., 1984; Weber et al., 2004). However, this cue was found to vary across languages (Fry, 1955; Kumar & Bhat, 2009; Lieberman, 1960).

Loudness perception in individuals with sensorineural hearing loss has been noted to be different from that seen in normal hearing individuals (Al-Salim et al., 2010; Brand & Hohmann, 2001; Buus & Florentine, 2002; Hellman & Meiselman, 1993; Plack et al., 2004; Robinson & Gatehouse, 1996; Serpanos & Gravel, 2000, 2004). Buus and Florentine (2002) revealed that in individuals with cochlear hearing loss, loudness growth was like normal hearing individuals at low sensation levels. However, at higher levels the loudness growth function was steeper in the former group. Other studies have also noted that the loudness growth curve was steeper and more variable at high frequencies where the hearing loss was more, compared to low frequencies where the loss was less (Hellman & Meiselman, 1993; Robinson & Gatehouse, 1996). Marozeau and Florentine (2007), who reviewed literature on loudness perception in individuals with hearing impairment, observed that there existed large variability in the loudness growth reported in studies. They also noted within the studies reviewed by them that some of the participants with hearing loss had rapid growth of loudness, some had softness imperception and others had both. Generally, the dynamic range of the individuals with sensorineural hearing loss was found to be reduced. Additionally, Al-Salim et al. (2010) reported that the slope of loudness growth curve was dependent on the hearing thresholds of individuals.

Besides hearing loss affecting loudness perception, settings in hearing aids were also reported to affect loudness perception. One of the hearing aid settings that was found to affect loudness perception was the use of compression (Gatehouse et al., 2006; Jenstad et al., 2000; Moore, 1996). While compression used in hearing aids was reported to improve speech clarity (Hawkins & Naidoo, 1993; Humes et al., 1999), loudness perception decreased significantly with increase in compression ratio (Neuman et al., 1998). Similarly, Musa-

Shufani et al. (2006) observed that with high compression ratios (3:1 & 8:1) and fast attack time (2 ms & 20 ms), the just noticeable interaural difference in intensity level worsened. Further, Kam and Wong (1999) noted that participants prefer loudness using wide dynamic range compression (WDRC) compared to a linear setting. Preference of WDRC settings over linear settings for audibility, loudness rating and comfortability was also reported by Jenstad et al. (2000). They observed that loudness growth function of the participants using WDRC was similar to that of normal hearing individuals rather than hearing aids with linear fitting.

Unlike the above studies, variations in loudness growth among hearing aid users with mild to severe hearing impairment was reported by Shi et al. (2007). They noted that most of their participants had a shallow loudness growth compared to the loudness growth curve of normal hearing individuals for a 2000 Hz warble tone, indicating over compression. Additionally, it was seen that in half their hearing aid participants the loudness growth was steep for a 500 Hz warble-tone compared to the normal loudness growth curve, implying under compression. These listeners were not satisfied with their aided loudness perception. The study highlighted that compression in hearing aids had an impact on loudness growth, which varied as a function of the frequency of the stimuli.

Thus, the review on hearing aids indicates that using appropriate compression settings, most hearing aid users could perceive loudness similar to normal hearing individuals. However, it was also reported that compression led to over compression or under compression, adversely affecting loudness perception. This variation in loudness growth perception was attributed to differences in hearing aid fitting.

As observed in hearing aid users, loudness perception is reported to be affected in those using cochlear implants (Kordus & Żera, 2017; Saki et al., 2015; Steel et al., 2014; Tak & Yathiraj, 2019a, 2021). While the benefits of cochlear implant in the development of language in children with hearing impairment is extensively reported in literature (Gagnon et al., 2020; Geers et al., 2017; Hammes et al., 2002; Lu & Qin, 2018; Niparko et al., 2010; Ruben, 2018; Sundaresan & Martina; Svirsky et al., 2000; Yoshinaga-Itano et al., 2018), its use in loudness perception is not given much importance. Loudness perception through cochlear implants has been mainly noted to be influenced by current amplitude and pulse width (Chatterjee et al., 2000; Pfingst et al., 1995; Smith & Finley, 1997; Zeng et al., 1998). Chatterjee et al. (2000) reported that loudness is also dependent on phase duration and electrode separation. Further, Bierer and Nye (2014) noted that factors such as electrical dynamic range and thresholds affect loudness perception through cochlear implants. Zeng and Shannon (1994) also noted that the frequency of the stimuli affected loudness perception through cochlear implants.

It is known that a maximum of 30 dB of an input acoustical signal is mapped in the output range between the threshold and the maximum stimulation level in a cochlear implant (Skinner et al., 1997). Thus, a wide acoustical intensity range is coded within a limited electrical dynamic range using compression. The impact of this compression on loudness perception has been studied mainly in adults (James et al., 2002; Kordus & Żera, 2017; Steel et al., 2014) and research on children is limited (Tak & Yathiraj, 2020). This loudness perception has been evaluated using electrical stimuli as well as acoustical stimuli.

Loudness perception through cochlear implants, measured using electrical stimuli, was noted to be comparable to loudness perception in normal hearing individuals (Steel et al., 2014). Busby and Au (2017) observed that cochlear implantees required different median current levels to perceive a particular loudness category. They noted that by using scaled electric current to eliminate difference in dynamic range, loudness growth was made uniform across participants. They also reported that loudness scaling using electrical stimulation in cochlear implantees was similar to that seen in normal hearing individuals for acoustical stimulation. However, Anzalone and Smith (2017) and Kordus and Żera (2017) noted great variability in loudness growth perception across participants using cochlear implants.

Intensity discrimination of electric stimuli was observed to vary depending on the absolute threshold, dynamic range and electrode pitch ranking by Nelson et al. (1996). They observed that higher the threshold, smaller was the Weber fractions, indicating greater sensitivity to intensity change. Additionally, those who had larger dynamic range, also had larger weber fraction, indicating poorer sensitivity to intensity change. Individuals with the best pitch discrimination ability had better intensity discrimination ability too. They also found that at lower intensities, the differential limen for intensity was poor but at higher intensities in the dynamic range, the differential limen improved.

Galvin III and Fu (2009) reported that loudness discrimination was poorer for high pulse stimulation rate than low pulse stimulation rate, especially at low stimulation levels. Similarly, Azadpour et al. (2018) also found loudness discrimination was affected by pulse rate with the just noticeable difference for loudness being higher by 60% for a stimulation rate of 3000 pulse per second than for a stimulation rate of 500 pulse per second.

Besides studying loudness growth in cochlear implantees using electrical stimuli, studies have also evaluated it using acoustical stimuli. Using acoustical signals, Saki et al. (2015) as well as Tak and Yathiraj (2019a) noted that intensity discrimination was poorer for participants using cochlear implants when compared to normal hearing participants. While the former study was done on adult cochlear implant users, the latter study was conducted on children. Tak and Yathiraj (2021) also noted that children using cochlear implants were poorer in relative loudness judgment compared to typically developing children.

From the review of literature, it can be noted that loudness perception is affected in individuals with hearing loss using listening devices. Their perception of loudness has been noted to vary depending on the hearing aid fitting parameters / cochlear implant map parameters. Most of these studies have been done on adults and studies on children are sparse.

1.1 Need for the study

1.1.1 Need to study loudness perception

Loudness perception is essential in day-to-day life for the perception of relative distance (Ashmead et al., 1990; Coleman, 1963; Guo et al., 2019; Strybel & Perrott, 1984), emotions (House, 1990; Laukkanen et al., 1996; Sauter et al., 2010; Whiteside, 1999), and stress (Lieberman, 1960). It was noted by Ashmead et al. (1990) that for reference distances of 1 m and 2 m, intensity cues to judge relative distance was possible only when the difference was 6% of the reference distance. Whereas, when intensity cues were not provided, 16% difference was needed to perceive the difference in relative distance. Further, Strybel and Perrott (1984) and Guo et al. (2019) noted that if intensity cues were provided, the thresholds for relative distance perception was better when the reference distance was farther than when the distance was nearer.

Loudness cues have also been found to assist in the perception of emotions. Whiteside (1999) noted that higher energy was observed with emotions such as happiness and elation compared to sadness. Laukkanen et al. (1996) reported that enthusiasm and anger were associated with increased fundamental frequency as well as sound pressure level. Several other studies have also demonstrated that loudness cues were used to differentiate various emotions (Davitz, 1964; Fónagy, 1981; House, 1990; Sauter et al., 2010).

The use of loudness cues for the perception of stress has been documented from the 1950s. Intensity was accepted as a major cue for the perception of stressed syllable in words (Fry, 1955, 1958). Lieberman (1960) also noted that for the perception of stress in English, besides frequency cues, amplitude cues were also important. Other researchers (Bull et al., 1984; Eilers et al., 1984; Weber et al., 2004) also found that intensity cues were required for the perception of stress. However, studies have demonstrated that perception of stress depends on the language being studied (Fry, 1955; Kumar & Bhat, 2009; Lieberman, 1960).

From the above literature it can be seen that loudness cues are utilised for perception of day-to-day acoustic signals. It is noted that loudness cues are used for non-verbal as well as verbal information. For verbal purposes, loudness cues have been used for the perception of segmental as well as suprasegmental cues. Most studies on loudness perception have been done on adults, and they have reported that loudness perception varies depending on the language being studied. Hence, further research on loudness perception requires to be carried out.

1.1.2 Need to study loudness perception in typically developing children

Loudness perception is known to vary as children mature (Werner & Gray, 1998). It has been noted by Maxon and Hochberg (1982) that typically developing children as young as 5 years are able to carry out activities to measure difference limen for intensity. It was also noted by them that their participants were able to obtain adult like responses by 5 years of age. Other researchers (Bond & Stevens, 1969; Collins & Gescheider, 1989; Ellis & Wynne, 1999) have also noted that children had similar loudness perception as adults. However, they observed the responses of children were more variable at lower and the upper extremes.

In order to obtain information about the loudness perception ability of children having hearing impairment, their performance requires to be compared with that of typically developing children. This will throw light on the difficulties children with hearing impairment have in comparison with typically developing age-matched children. Further, loudness perception has been noted to vary depending on the method being used (Hellman & Zwislocki, 1968; Jenstad et al., 1997; Marozeau & Florentine, 2007). Hence, to study loudness perception in children using listening devices, it is essential to study loudness perception in typically developing children using the same method.

1.1.3 Need to study loudness growth in children using hearing aids and children using cochlear implants

Loudness growth measurement has been utilized to provide optimum gain through hearing aids using different procedures (Cox & Gray, 2001; Ellis & Wynne, 1999; Kiessling et al., 1996; Moore et al., 1999; Valente & VanVliet, 1997). Similarly, for setting current levels in cochlear implants, loudness growth perception measurement was also recommended to be used (Anzalone & Smith, 2017; Gordon et al., 2004; Potts et al., 2007). Besides evaluating loudness perception to set programmes / maps of listening devices, children with hearing loss, like their hearing counterparts, require to use loudness growth cues to perceive relative distance of acoustical stimuli (Ashmead et al., 1990; Coleman, 1963; Guo et al., 2019; Strybel & Perrott, 1984).

Most studies on loudness growth perception through hearing aids (Gottermeier & De Filippo, 2018; Jenstad et al., 2000; Olsen et al., 1999; Shi et al., 2007) as well as cochlear implants (Anzalone & Smith, 2017; Bierer & Nye, 2014; Busby & Au, 2017; Kordus & Żera, 2017; Steel et al., 2014) were conducted on adults, who had acquired hearing loss. Their prior knowledge would have helped the adults respond to loudness perception tests. However, such prior knowledge would have been absent in children with congenital hearing loss. Anzalone and Smith (2017) also noticed that there were differences in loudness growth functions between pre-lingually deafened and post-lingually deafened participants using cochlear implants. Thus, the findings obtained in adults cannot be extrapolated to children. Research using loudness perception techniques in children is sparse and hence requires to be assessed.

1.1.4 Need to study intensity discrimination in children using hearing aids and children using cochlear implants

Besides using loudness perception measures in fitting or programming of hearing aids / cochlear implants, loudness is used for perception of different day-to-day signals. Intensity discrimination helps individuals differentiate emotions such as happiness, elation (Whiteside, 1999), enthusiasm, anger (Laukkanen et al., 1996) and sadness (Sauter et al., 2010). Further, individuals with sensorineural hearing loss were noted to have poor perception of emotions (House, 1990; Oster & Risberg, 1986) and stress (Rubin-Spitz et al., 1986). Individuals with hearing loss were observed to continue having difficulty in perceiving emotions (House, 1994; Luo et al., 2007; Schmidt et al., 2016), and stress (Most & Peled, 2007) using listening devices such as hearing aids and cochlear implants. A reason for this difficulty could be due to difficulty in intensity discrimination.

It has been demonstrated that adults using hearing aids have difficulty in intensity discrimination (Devi et al., 2017; Philibert et al., 2002; Robinson & Gatehouse, 1995; Whitmer & Akeroyd, 2011). Similar difficulties were also reported by Saki et al. (2015) in individuals using cochlear implants. They too noted that adults using cochlear implants had poorer intensity discrimination thresholds compared to normal hearing listeners. Recently, Tak and Yathiraj (2021) noted that children using cochlear implants as well as children using hearing aids were not as good as typically developing children in judgment of relative loudness of day-to-day objects / situations. Thus, while information on intensity discrimination through hearing aids and cochlear implants is available in adults, similar research in children is limited. Hence, there is a need to further study intensity discrimination thresholds of children with hearing loss while using listening devices.

1.1.5 Need to study loudness perception with different hearing aid fitting parameters

It is well established that hearing aid fitting parameters such as compression ratio, compression threshold, attack time and release time affect speech perception (Boike & Souza, 2000; Jenstad et al., 1999; Jenstad & Souza, 2005; Neuman et al., 1994). It is also been observed that loudness perception is compromised due to fitting parameters in hearing aids such as compression ratio, attack time and release time (Dillon, 2001; Jenstad et al., 2000; Kuk, 1996; Musa-Shufani et al., 2006; Neuman et al., 1998). Neuman et al. (1998) noted that as the compression ratio in hearing aids increased, loudness rating decreased. It was also reported by Jenstad et al. (2000) that differences occurred in the exponent of loudness growth functions obtained with a linear setting and with a wide dynamic range compression setting in hearing aids. However, the effect of compression parameters was majorly studied on adults. It is speculated that lack of prior experience to loudness cues in children would make their loudness perception different from that of post-lingual adults. Thus, the magnitude of loudness perception problems seen in children may differ from what is seen in adults, making it necessary to study the impact of hearing aid compression in children. This information will throw light on the knowledge of children regarding different aspects that require loudness perception such as distance of a sound, perceptions of emotions that differ in loudness, and stress.

1.2 Aim of the study

The study aimed at evaluating loudness growth and intensity discrimination in children using cochlear implants and children using hearing aids, as well as study the effect of compression parameters on loudness perception in children using hearing aids.

1.3 Objectives

The objectives of the study were:

1. To study the effect of random and sequential order methods of stimulation on loudness growth perception.
2. To study loudness growth perception in children wearing their own prescribed hearing aids, linear hearing aids, and non-linear hearing aids.
3. To study intensity discrimination in children wearing their own prescribed hearing aids, linear hearing aids, and non-linear hearing aids.
4. To compare intensity required to identify loudness levels (loudness growth) between:
   a. Typically developing children, children using cochlear implants, and children using their own prescribed hearing aids,
   b. Typically developing children, children using cochlear implants, and children using hearing aids with linear setting,
   c. Typically developing children, children using cochlear implants, and children using hearing aids with non-linear setting.
5. To compare intensity discrimination between:
   a. Typically developing children, children using cochlear implants, and children

using their own prescribed hearing aids,

b. Typically developing children, children using cochlear implants, and children using hearing aids with linear setting,

c. Typically developing children, children using cochlear implants, and children using hearing aids with non-linear setting.

1.4 Hypotheses

The null hypotheses formed to investigate the objectives of the study were as follows:

1. There is no significant difference between random and sequential order methods of stimulus presentation on loudness growth perception in:
    a. Typically developing children,
    b. Children using cochlear implants.
2. There is no significant difference in loudness growth perception between:
    a. Own prescribed hearing aids and linear hearing aids,
    b. Own prescribed hearing aids and non-linear hearing aids,
    c. Linear hearing aids and non-linear hearing aids.
3. There is no significant difference in intensity discrimination between:
    a. Own prescribed hearing aids and linear hearing aids,
    b. Own prescribed hearing aids and non-linear hearing aids,
    c. Linear hearing aids and non-linear hearing aids.
4. There is no significant difference in intensity required to identify loudness levels between:
    a. Typically developing children, children using cochlear implants, and children using their own prescribed hearing aids,

    b. Typically developing children, children using cochlear implants, and children using hearing aids with linear setting,
    c. Typically developing children, children using cochlear implants, and children using hearing aids with non-linear setting

5. There is no significant difference in intensity discrimination between:
    a. Typically developing children, children using cochlear implants, and children using their own prescribed hearing aids,
    b. Typically developing children, children using cochlear implants, and children using hearing aids with linear setting,
    c. Typically developing children, children using cochlear implants, and children using hearing aids with non-linear setting.

2. Review of Literature

Advancement in technology of hearing devices has made it possible to reduce the handicapping effects of hearing loss. Despite this advancement, perception of acoustical signals through hearing devices has been observed to not replicate natural hearing (Blamey & Martin, 2009; Gatehouse & Noble, 2004; Shi et al., 2007; Souza, 2002). Hence, researchers continue to probe and find ways in which listening devices can deliver acoustical signals that can mimic natural hearing. To improve perception through hearing devices, considerable research has been carried out regarding frequency cues (Gaudrain et al., 2016; Miller et al., 2016; Rader et al., 2016a; Rader et al., 2016b; Souza et al., 2013; Wiggins & Seeber, 2011; Wolfe et al., 2010) and temporal cues (Kong et al., 2016; Luke et al., 2015; Moberly et al., 2016; Stilp & Goupell, 2015; Tremblay et al., 2006; Won et al., 2015). However, research on the perception of loudness cues is relatively less (Blamey & Martin, 2009; Kordus & Żera, 2017; Shi et al., 2007). Loudness perception is reported to be important for the perception of relative distance (Ashmead et al., 1990; Coleman, 1963; Strybel & Perrott, 1984), emotions (Fónagy, 1981; House, 1990; Laukkanen et al., 1996; Sauter et al., 2010; Whiteside, 1999), and stress (Fry, 1955, 1958; Lieberman, 1960). However, individuals using listening devices such as hearing aids and cochlear implants were noted to have difficulty in the perception of relative distance (Akeroyd, 2010; Mertens et al., 2013), emotions (House, 1994; Luo et al., 2007), and stress (Chin et al., 2012; Most & Peled, 2007). In order to make appropriate manipulations of intensity parameters in hearing devices meant for those with hearing impairment, studies have evaluated the factors that affect loudness perception in normal hearing individuals. The following review of literature focuses on the variables that impact loudness perception in normal hearing individuals as well as the perception of loudness by individuals using cochlear implants and those using hearing aids.

2.1 Variables that Impact Loudness Perception in Normal Hearing Individuals

The perception of loudness in normal hearing individuals is reported to depend on many stimulus related factors. Some of the factors reported in literature include intensity, frequency, duration, spectrum, bandwidth of a sound, and order in which stimuli are presented. Within each of these parameters, studies have evaluated loudness growth function and / or intensity discrimination in different age groups using different stimuli. The studies evaluating loudness growth function attempt to determine whether the growth was linear or exponential as well as whether the method of presentation had an impact on the responses. Studies have also evaluated intensity discrimination by varying specific acoustical parameters. However, the number of studies that evaluated this measure of loudness perception are relatively less. The variables that affect loudness growth and intensity discrimination are reviewed in detail below.

2.1.1 Intensity

It has been found that loudness increases with the increase in intensity (Bartoshuk, 1964; Fletcher & Munson, 1933; Robinson & Gatehouse, 1996; Stevens, 1955). One of earliest description of loudness was given by Fletcher and Munson (1933). They differentiated loudness level from loudness, explaining that the former was represented in dB, while the latter was expressed in units that were yet to be developed at that point of time.

Based on a review of literature, Stevens (1955) noted that for a 1000 Hz tone, a change in intensity by 10 dB was required to produce a perception of half or double the loudness of a signal. This was noted to be constant throughout the intensity range and was considered to indicate that loudness was a power function of intensity, with the exponent being 0.03. However, at low intensity levels, a given increase in intensity of a white noise produced greater change in loudness than that observed for a 1000 Hz tone. On the other hand, at the upper range the loudness of the white noise grew less rapidly with increase in intensity when compared to a similar increment in intensity of a 1000 Hz tone.

The perception of loudness was noted to be present at a very young age by Bartoshuk (1964) who studied the relation between the magnitude of cardiac responses and stimulus intensity in new-borns. Thirty-nine full-term new-borns were presented with a 1000 Hz tone at four different intensities. It was found that there was a linear relationship between heart rate response plotted on a logarithm scale and stimulus intensity in decibels. This finding was consistent with the power function between sensory magnitude and physical intensity demonstrated by Stevens (1955).

Robinson and Gatehouse (1996) measured loudness growth function of seven normal hearing younger adults (aged 18 to 35 years) and five normal hearing older adults (aged 57 to 84 years). The participants classified complex tones that ranged from 6 dB SL to a level below the loudness discomfort level on an eight-point rating scale. Both groups of normal hearing participants were found to rate the loudness in an exponential curve, having an exponent of 0.02. However, when the abscissa was converted to linear pressure and the power function was fitted, the power value ranged from 0.18 to 0.22 for normal hearing participants at 250 Hz and 3000 Hz.

Further, Rasmussen et al. (1998) also evaluated the long-term test-retest reliability of category loudness scaling of 16 adults with normal hearing (aged 20 to 52 years). The loudness growth for pure-tones (500 Hz, 1000 Hz, 2000 Hz, & 4000 Hz) that were changed in 1 dB steps was measured using a custom-made PC based audiometer. The stimuli were presented randomly between individually selected maximum stimulus levels and 5 dB below the thresholds. Using response-buttons, the participants who heard the stimuli through headphones, categorized the loudness on a seven-point scale (‘not heard’, ‘very soft’, ‘soft’, ‘OK’, ‘loud’, ‘very loud’, & ‘too loud’). The test was repeated after 8 to 29 days to estimate the reliability. Poorer test-retest reliability was found at the intermediate levels than at the louder and the softer levels. Also, the reliability was better at louder levels than at the softer levels. Overall, the standard deviation of the hearing levels at each category between the two sessions were not more than 10 dB. The test-retest reliability was not found to be dependent on the frequency of the pure-tones.

Thus, from the review, it was noted that loudness was a power function of intensity. At higher intensity levels, the growth in loudness for white noise was more gradual and was steeper at low levels. However, this trend was not seen for pure-tones (Stevens, 1955). The relation between the intensity and the loudness was noted to be present soon after birth. Further, the test-retest reliability was better at louder and softer loudness levels than at the intermediate loudness levels.

2.1.2 Frequency

Loudness perception as a function of frequency has been explained using equal loudness contours (Fletcher & Munson, 1933; Suzuki & Takeshima, 2004; Takeshima et al., 2003). Additionally, magnitude estimation and magnitude production methods have also been used to assess the impact of frequency of the stimuli on loudness perception (Hellman, 1976; Hellman & Zwislocki, 1968).

Close to a century ago, Fletcher and Munson (1933) discussed the relation between loudness level and frequency using a 1000 Hz reference tone. Based on equal loudness contours measured in normal hearing listeners, it was noted that from 300 Hz to 4000 Hz, the loudness level was approximately equal to the intensity level. Further, the authors also reported that below 125 Hz, the loudness level changed very rapidly with both changes in intensity and frequency.

Hellman and Zwislocki (1968) studied the impact of the frequency of tones (0.1, 0.25, & 1 kHz) on the growth of loudness using magnitude estimation and magnitude production tasks, in individuals with normal hearing. The stimuli were presented randomly within an intensity range of 4 to 70 dB SL though earphones. The steepness of loudness growth was maximum at 0.1 kHz, followed by 0.25 kHz and was least at 1 kHz. This pattern was explained by the higher spread of excitation at lower frequencies.

Similar to Hellman and Zwislocki (1968), loudness growth function for tones of 1000 Hz and 3000 Hz were measured by Hellman (1976) using magnitude estimation and magnitude production on nine normal hearing young adults. The stimuli were presented through earphones in a random order, within the dynamic range of the participants. The magnitude production task resulted in steeper power function (exponent of 0.70) at 1 kHz than at 3 kHz (exponent of 0.67). On the other hand, for the magnitude estimation task, the power function of loudness growth at 1 kHz was less steep (exponent of 0.54) than at 3 kHz (exponent of 0.57). Further, the power functions obtained using the magnitude production task was found to be steeper than the magnitude estimation task.

Takeshima et al. (2003) measured equal loudness counters for the pure-tones 125 Hz and 1 kHz on ten normal hearing adults aged 19 to 32 years. The participants were instructed to compare the loudness of two tones and equal loudness counters were obtained at 5, 10, 15, 20, 25, 30, 40, 50 and 70 phons. At 125 Hz, above 20 phons the equal loudness curve was linear with a slope of 1.3. This was interpreted to indicate that the function followed the Steven's power law at this range with a power exponent that was 1.3 times greater than that of 1 kHz. A narrower spacing of equal loudness contour was found to occur at 125 Hz compared to 1 kHz above 20 phons. It was also found that at lower levels below 20 phons, the contour exhibited wider spacing than at the higher levels.

Thus, studies on the relation between frequency and loudness indicated that at lower frequencies the loudness growth was much faster than at higher frequencies. However, the effect of frequency on loudness growth function was found to vary depending on the measurement method.

2.1.3 Duration

Loudness is reported to increase with increase in duration till 200 ms. Studies on the effect of duration on loudness perception have been majorly carried out on adults (Epstein & Florentine, 2005, 2006; Florentine, 1986; Florentine & Poulsen, 1996).

To estimate the impact of stimulus duration on intensity discrimination, Florentine (1986) evaluated three young adult females aged 22 to 24 years using pure-tones (250 Hz, 1000 Hz, & 8000 Hz). The discrimination was obtained at three intensities (85 dB SPL, 65 dB SPL, & 10 dB SL, which was approximately 40 dB SPL) for stimuli that were randomly presented monaurally through headphones at durations that ranged from 2 ms to 2 s. Using a two-alternative forced choice method, the listeners were asked to indicate which interval corresponded to a more intense sound. It was noted that the thresholds decreased with the increase in duration till 2 s for the 1000 Hz and 8000 Hz tones. However, for the 250 Hz tone, the intensity level discrimination decreased with increase in durations between 500 ms to 1 s. Also, at the higher intensity level, the thresholds were lesser as compared to the lower intensity levels.

In a subsequent study, Florentine and Poulsen (1996) measured loudness perception as a function of duration of the signal in six normal hearing adults (19 to 28 years). The participants were required to carryout a loudness matching task using a 1 kHz tone and a broadband noise, each having durations of 5 ms, 30 ms and 200 ms. The listeners were asked to match a short stimulus having a fixed level with another long stimulus that was varied till a loudness match was achieved. The level difference between the two stimuli (fixed & variable) at equal loudness, termed as temporal integration, was reported to vary nonmonotonically with the level for the tones and noise. Temporal integration was found to be maximum when the short tone was around 56 dB SPL and when the short noise was around 76 dB SPL. The results also indicated that temporal integration was maximum when 5 ms and 200 ms stimuli were compared. This was followed by 5 ms and 30 ms stimuli. However, the temporal integration was least when the stimulus pair of 30 ms and 200 ms were compared.

Epstein and Florentine (2005) evaluated cross-modality loudness matching on nine normal hearing individuals aged 20 to 46 years. Each individual was required to match the loudness of a 1 kHz tone having durations of 5 ms or 200 ms. Additionally, they were asked to match the loudness of two tones at 5 ms and 200 ms, keeping one fixed and other varying at different levels. The level difference between the two equally loud tones having durations of 5 ms and 200 ms was compared with the level difference between two tones with equal length. The obtained data was then used to derive loudness functions at 5 ms and 200 ms. The cross-modality matching function was found to be shallower at moderate levels for both 5 ms and 200 ms tones. Like the earlier studies, it was observed that temporal integration was maximum at moderate levels as compared to low and high levels.

In an extension of their earlier study, Epstein and Florentine (2006) estimated loudness on nine normal hearing adults. Ten magnitude estimates were obtained for each level and duration (5 ms & 200 ms) in 5 dB steps that ranged from 5 dB SL to 100 dB SPL for a 200 ms tone and to 110 dB SPL for a 5 ms tone. They too noted that temporal integration varied nonmonotonically with level and was maximum at a moderate level of intensity.

From the literature it can be observed that loudness increases with duration. However, this growth was found to be nonmonotonically at different signal levels. At moderate levels, the temporal integration was observed to be more and the loudness growth was slow. This was found to resemble the mechanical properties of the basilar membrane.

2.1.4 Bandwidth

The effect of bandwidth on loudness perception had been reported in literature since the early 1930s. One of the first studies on loudness provided information about the loudness of a complex tone in relation to the loudness of each its components (Fletcher & Munson, 1933). Further, other authors (Leibold et al., 2007; Zwicker et al., 1957) also studied the effect of increase in bandwidth on loudness.

Zwicker et al. (1957) studied the loudness of a four-tone complex that varied in bandwidth, centred at 0.5, 1 or 2 kHz. Ten adults were required to match the loudness of these signals to a single pure-tone. They found that the conditions in which the frequency separation was less than one critical band, the loudness was independent of the bandwidth. As the frequency separation exceeded the critical band, the loudness increased.

More recently, Leibold et al. (2007) conducted an experiment on seven adults aged 18 to 40 years to investigate the effect of increasing band-widening on loudness perception. The participants heard multi-tone complexes having bandwidths varying from 46 Hz to 2119 Hz, at 60 dB SPL for 300 ms. The six logarithmic spacing conditions were used, having frequency ratios ranging from 1.012 between adjacent components to 1.586. The spacing corresponded to bandwidths of 46 Hz to 2119 Hz. For the narrowest bandwidth condition, all the five components of multi-tone complex fell within a single critical band centred at 1000 Hz. The participants were asked to match the loudness of the five multi-tone complexes centred at 1 kHz with the loudness of a 1 kHz pure-tone. It was found that if the components increased within a critical band the loudness of the multi-tone complex was independent of the bandwidth. However, when the components exceeded the critical band, the loudness increased. It was also found that the loudness increased at a rate of 2.8 dB/octave with increasing bandwidth.

The studies on the effect of the bandwidth agree that with increase in the bandwidth of stimuli, the loudness level also increased. This has been observed for narrow band noise compared to broadband noise as well as for multi-tone complexes.

2.1.5 Order of stimulus presentation

It has been demonstrated that loudness perception varied depending on the order of stimulus presentation (Baird et al., 1991; Beattie et al., 1997; Jenstad et al., 1997). This has mainly been studied in adults using pure-tones, warble-tones as well as speech.

Baird et al. (1991) estimated the loudness growth function in15 normal hearing adults, using a systematic and an irregular order of stimulus presentation. The loudness growth function was estimated using a 1000 Hz tone having 12 sound pressure levels presented monoaurally through a headphone. The effect of presenting the stimuli in an ascending-descending order and in a balanced-irregular order was studied. It was noted that the exponent obtained using the systematic order of stimulus presentation was 0.60, but was noted to be 0.29 using an irregular order of stimulus presentation. Also, the authors noted that the variability of the power functions was greater in the systematic order of stimulus presentation than in the irregular order of stimulus presentation. It was concluded that the subjects tended to judge their responses based on the maximum, minimum and sound pressure of the previous stimulus. This assimilation effect in loudness judgement was seen in both methods of stimulus presentation.

The effects of ascending, descending and random order of presenting warble-tones (500 Hz & 3000 Hz) and monosyllabic words on loudness growth was studied by Beattie et al. (1997) on 31 normal hearing adults. In addition, they also evaluated the correlation between the warble-tones and speech. They observed that the descending order of stimulus presentation usually required higher SPL values for each loudness category compared to the ascending order of presentation. The random order of presentation resulted in the very soft to comfortable-soft loudness categories having similar SPL as the ascending procedure. However, at the higher loudness categories, the random approach required higher SPL values than the ascending approach. Further, the random order approach required lower SPLs than the descending order approach for the categories ‘very soft’ through ‘comfortable’. On the other hand, at the higher loudness categories (‘loud-okay’ through ‘uncomfortably loud’) the random approach needed higher SPLs than the descending approach. The authors recommended the use of the random order of stimulus presentation as it had lesser bias. The study also demonstrated that there was no correlation between the loudness growth function of warble-tones and speech.

The effect of stimulus order presentation and the presence of a higher referent tone before the stimulus on loudness growth function was studied by Jenstad et al. (1997). Forty normal hearing adults were tested at 500 Hz, 1000 Hz, 2000 Hz, and 4000 Hz using insert earphones. The participants were divided into two groups, with Group 1 being tested with only one stimulus at a time and Group 2 being tested with one higher referent tone prior to the stimulus tone. The stimulus levels were presented in sequential order (ascending or descending) and random order. The loudness growth function was fitted to a power function. When the mean exponent of the loudness growth function was compared across the groups, it was noted that change in loudness of low-level stimuli was slow when the referent tone was not presented than when it was presented. Further, it was observed that the change in a low loudness level was slower when the stimulus was presented sequentially than when it was presented in a random order. Also, the stimuli presented in the ascending order had a higher exponent value compared to the descending order of presentation.

Thus, the studies on the order of stimulus presentation indicate that the power function using sequential order of stimulus presentation was more variable than the random order method. Using a sequential order method, the change in loudness at low levels were noted to be slower than the random order method. These findings were ascribed to the response bias as the knowledge of maximum and minimum level as well as the level of the previous presentation changed the perception of loudness among listeners.

2.1.6 Effect of Age of Participants on loudness perception

Loudness perception has been studied as a function of the age of participants. The comparison has mainly been done between children and adults (Bond & Stevens, 1969; Collins & Gescheider, 1989; Ellis & Wynne, 1999).

Bond and Stevens (1969) compared the ability of five children and five young adults in a cross-modality procedure that involved matching brightness of light to loudness of a 500 Hz tone. The participants were seated at a distance of 3 feet from the visual stimuli and the auditory stimuli were presented through earphones. The 500 Hz tone was presented randomly at eight different levels ranging from 40 dB to 110 dB SPL. The participants were asked to control the brightness of a light to match it to the loudness perceived by them. It was noted that the loudness growth functions of the two groups were similar. However, the inter-quartile range indicated that the children had slightly more variability than the young adults.

Similarly, Collins and Gescheider (1989) also compared 11 children (4 to 7 years) with 12 young adults using a cross-modality matching and magnitude estimation method of loudness function. The cross-modality matching method required the participants to match the length of lines to the loudness of the stimuli. The magnitude estimation task was obtained with the participants expressing their perception of loudness with a number. A 1000 Hz tone was presented through earphones in 10 dB steps within a range of 10 to 80 dB SL, in a quasi-random order. The geometric means of the responses were calculated for both methods. The loudness growth function of children was found to approximate that of the adults. An exception to this was at the lower intensities for the amplitude magnitude estimation task, where the children were found to give inaccurate responses.

Ellis and Wynne (1999) compared the loudness growth of 20 children (age range = 7 to 12 years) and 20 adults (age range = 21 to 26 years) using a half-octave band automatic procedure, available in the Resound P3 hearing aid fitting system. The stimuli consisted of half-octave bands of periodic noise centred at 500 Hz, 1 kHz, 2 kHz and 4 kHz. The stimuli were presented randomly between the dynamic range of each participant and the participants were expected to categorize the loudness of the sound on a 7-point rating scale. The participants were instructed to point to drawings of faces that described the loudness of the stimuli. The results indicated that for the ‘Too soft’ category there was a significant difference between the two age groups at noise centred at 500 Hz, 1000 Hz and 2000 Hz but not at 4000 Hz. Children were noted to judge the stimulus ‘Too soft’ at intensity levels that were greater than the adults. Similar significant differences were obtained for the ‘Too loud’ loudness category, but with the children needing lower intensities than the adults. Also, the variance was greater for children than adults. The test-retest differences within the sessions were not significant for both the groups.

Unlike the above studies, Serpanos and Gravel (2004) found no difference in loudness perception between children and adults having normal hearing. They evaluated 22 children (aged 4 to 12 years; mean age = 7.4 years; SD = 2.4 years) and 10 adults (mean age = 34 years; SD = 12 years) with normal hearing. Using a custom designed computer software, half-octave noise bands centred at 2000 Hz were presented through earphones. The stimuli were presented randomly between 20 dB SPL to 90 dB SPL in 10 dB step sizes. The loudness growth functions were derived using two methods, one where the participants matched the length of lines with the loudness of the sound. In the other method they adjusted the intensity of the stimulus to have a loudness level that matched the length of a line. The geometric means of the two stimulus levels for two methods were obtained. No statistically significant difference between the two groups was obtained.

Hence, the above studies regarding the effect of age on loudness perception generally observed that both adults and children have similar loudness growth functions. However, children were found to have more variability in responses than adults. Also, at low and high levels both the groups were noted to be different.

The studies reported in literature on different variables that affect loudness perception indicate that there are various parameters that have an impact on normal hearing individuals. Loudness was noted to vary depending on the stimulus related parameters such as intensity, frequency, duration, bandwidth and the order in which they are presented. Additionally, subject related factors were also found to impact loudness perception, one being the age of the listeners. Another subject related factor that has been found to impact loudness perception is the hearing ability of individuals.

2.2 Loudness Perception in Individuals with Sensory Neural Hearing Loss

The effect of hearing loss on loudness perception has been studied mainly in adults (Brand & Hohmann, 2002; Buss et al., 2009; Hellman & Meiselman, 1993; Robinson & Gatehouse, 1996). A few studies have also studied it in children (Serpanos & Gravel, 2000, 2004). Among individuals with hearing loss, loudness perception was noted to vary depending on the method used (Marozeau & Florentine, 2007), the degree of hearing loss of the individuals (Al-Salim et al., 2010; Hellman & Meiselman, 1993) and the slope of the audiogram (Hellman & Meiselman, 1993). Most studies have compared the performance of those with hearing loss with normal hearing individuals. While a few studies evaluated loudness perception using a loudness growth function, others evaluated it using intensity discrimination. Details of these studies are provided below.

Hellman and Meiselman (1993) compared the rate of loudness growth of 32 normal hearing listeners and 20 individuals with bilateral moderate-to-severe sloping high frequency hearing loss, aged 56 to 72 years. The normal hearing listeners were tested with tone-bursts that varied in frequency from 500 to 2000 Hz and the listeners with hearing loss were tested with tone-bursts varying from 500 to 3250 Hz. The stimuli were presented randomly through earphones. The loudness growth was estimated using amplitude magnitude estimation, cross-modality matching and magnitude production methods. The results indicated that for the normal hearing participants the mean slope of loudness growth curve obtained within 35 to 91 dB SPL was approximately 0.60. Although, the participants with hearing loss had a mean slope close to 0.63 at 500 Hz, for higher frequencies the slope increased and was more variable with increase in the degree of hearing loss.

Robinson and Gatehouse (1996) established loudness growth function for older adults (54 to 82 years) with sloping sensorineural hearing loss. These participants were studied in addition to a group of normal hearing younger adults (18 to 35 years) and a group of older adults (57 to 84 years). Using complex tones centred at 250 Hz or 3000 Hz for loudness categorization on an 8-point rating scale, it was noted that data of the older adults with hearing loss fitted a power function of 0.52 at 3000 Hz. However, the power ranged from 0.18 to 0.22 for a groups of normal hearing children and adults. Also, it was noted that the inter-subject variability for the adults with hearing impairment was higher at 3000 Hz relative to 250 Hz. Test-retest reliability between sessions indicated that the intra-subject variability reduced with the increase in level. This was seen for all the three groups and both the frequencies.

The growth of loudness in children with moderate to severe sensorineural hearing loss (n = 8; aged 4 to 12 years) was compared with normal hearing children (n = 8; aged 4 to 12 years) by Serpanos and Gravel (2000). A cross-modality matching procedure was used where the length of lines was associated with the loudness of sounds having different intensity. The acoustic stimuli consisted of 1/3rd octave, narrow-band noise centred at 500 Hz and 2000 Hz. The normal hearing children were tested with the intensity varying from 20 dB HL to 90 dB HL in 10 dB steps. The children with hearing loss were evaluated with intensity levels that were individually determined by dividing the dynamic range of each child by eight. The intensity of each stimulus was presented randomly. The loudness growth curve for the children with hearing loss was noted to be steeper than that of the normal hearing children. However, at higher stimulus levels, most of the children with hearing impairment achieved normal loudness perception. Also, in the children with hearing loss, the slope was higher and loudness growth pattern was steeper at frequencies where their thresholds were high. Similar findings were noted in a subsequent study by Serpanos and Gravel (2004), where 14 children (aged 4 to 12 years) with mild to severe sensorineural hearing loss were evaluated.

The effect of hearing loss, centre frequency and bandwidth on loudness perception was evaluated by Brand and Hohmann (2001). They used narrow-band noise centred at 250 Hz and 4 kHz and a broadband noise. Loudness growth was evaluated using a categorical loudness scaling on eight normal hearing individuals (24 to 39 years) and eight individuals with severe sensorineural hearing loss (16 to 72 years). In the normal hearing group, an upwardly concave loudness function was observed for the narrow band noise and linear functions for the broad band noise. Generally, the broad band stimulus was louder compared to the narrow band stimuli. This was ascribed to spectral summation. This spectral summation effect was found to be more prominent at a moderate level as compared to low and high levels. Among the listeners with hearing impairment, most showed increased slope due to recruitment, while some showed less upwardly concave function for the narrow band noise that tended to be more linear. However, there was a great variability among listeners in the study.

Like the earlier studies, Buus and Florentine (2002) evaluated the loudness growth function on five adults (2 females & 3 males) with mild to moderate cochlear hearing impairment. The participants were required to match the loudness of a 1600 Hz tone and complex tones centred around 1600 Hz with four or ten tone complexes having a constant stimulus duration of 500 ms, near their thresholds. It was found that loudness functions near the threshold exhibited a slope value within a normalized range but enlarged with greater exponent at around 20 dB SL. It was also observed that at threshold, the loudness doubled for every 16 dB loss of hearing. Thus, the study revealed that the loudness growth was like normal hearing individuals in individuals with cochlear hearing loss at low sensation levels. However, at higher levels the loudness growth function was steeper in individuals with hearing loss as compared to normal hearing individuals. The authors attributed this finding to loss of compression at moderate levels due to loss of outer hair cells.

Plack et al. (2004) studied the basilar membrane response to a tone in individuals with mild to moderate hearing loss. A psychophysical procedure was used to estimate the input/output curve of the basilar membrane of 16 normal hearing individuals (aged 19 to 37 years) and nine individuals (aged 54 to 68 years) with mild to moderate sensorineural hearing loss. The effect of compression and gain was studied for low level (10 dB SL) 4000 Hz tone with a 2200 Hz off-frequency masker and a 4000 Hz on-frequency masker. It was found that in the normal hearing individuals, the gain was linear at low levels and was compressive at the medial level. On the other hand, in individuals with hearing loss, a systematic reduction in gain occurred with increase in hearing loss.

Marozeau and Florentine (2007) reviewed four studies to compare four different methods of loudness perception. The four methods included absolute magnitude estimation (Hellman & Meiselman, 1990), cross-modality matching, a method that they subsequently published (Marozeau & Florentine, 2009), categorical loudness scaling (Brand & Hohmann, 2001), and binaural loudness summation (Whilby et al., 2006). From each of the studies, the data of four individuals with moderate to severe degrees of cochlear hearing impairment were analyzed to compare the loudness functions with the averaged data of normal hearing individuals of each study. Within and across the studies, it was observed that there existed large variability in the loudness growth among those with hearing impairment. Additionally, they reported of differences in the average loudness growth among normal hearing participants across the studies. It was also noted in each of the reviewed studies that the loudness functions of some listeners varied in terms of steepness, and/or softness imperception. However, the participants had no difficulty in carrying out the loudness growth task. Thus, the authors dispelled the idea that all individuals with cochlear hearing impairment perceived loudness in a similar fashion. It was suggested that care must be taken regarding the method while comparing the loudness function across studies.

Al-Salim et al. (2010) examined the relationship between loudness measured using categorical loudness scaling method and the thresholds of 74 participants aged 11 to 76 years. Among them 16 had normal hearing and the remaining 58 had hearing loss with thresholds up to 75 dB HL. The participants judged the loudness of three 1000 ms pure-tones (1 kHz, 2 kHz, & 4 kHz) presented within their dynamic range through insert earphones. The responses were obtained on a scale that consisted of 11 coloured horizontal bars with six labels ('Can't hear, Soft, Medium, Loud, Very Loud, & Too loud), alternating with five un-labelled bars. The bars were assigned arbitrary numbers from 0 to 50 in steps of 5, with each set representing a categorical unit. The correlation of slopes of the categorical loudness scaling functions with thresholds was assessed. Although a significant correlation was noted at all frequencies, the correlation was higher at 1 kHz and 2 kHz than at 4 kHz. It was also noted that the slope of the low-level of the function varied systematically with threshold. The slope increased as the threshold increased. For participants with hearing loss, the function coincided with normal loudness near the medium loudness level. For loud sounds, the two groups tended to assign the same categories for similar intensities.

The review on loudness perception of individuals with hearing loss indicates that it is different from that seen in normal hearing individuals. Those with a hearing loss were usually found to have loudness growth functions that were steeper than that obtained by normal hearing listeners. This was observed at the low and medium intensity levels. However, at higher intensity levels, individuals with hearing loss perceive the loudness similar to that of normal hearing individuals. The loudness perception problems for softer sounds in those with hearing loss has been attributed to the loss of compressive non-linearity action of the basilar membrane. This loss of perception of loudness was observed to vary considerably across individuals with cochlear hearing loss.

2.3 Loudness Perception in Individuals Using Cochlear Implants

The advent of cochlear implant is known to have made it easier for individuals with severe to profound hearing loss to access auditory signals. Acoustical sounds are reported to have a dynamic range of 120 dB within which normal hearing individuals perceive sounds (Borg & Zakrisson, 1973). However, when converted for use in cochlear implants, this wide dynamic range is noted to be coded within an electric dynamic range of 20 dB (Bierer & Nye, 2014; Chua et al., 2011; Skinner et al., 1997; Zeng et al., 2002). Manufacturers have used various compression strategies to code this wide acoustic dynamic range into cochlear implants (Shannon, 1985; Vaerenberg et al., 2014; Zhang & Zeng, 1997). However, it is reported that loudness perception in cochlear implants is mainly influenced by the current amplitude and pulse width (Chatterjee et al., 2000; Pfingst et al., 1995; Smith & Finley, 1997; Zeng et al., 1998). Loudness perception was also noted to be dependent on electrode separation (Chatterjee, 1999; Chatterjee et al., 2000), and electrical dynamic range (Anzalone & Smith, 2017; Bierer & Nye, 2014; Busby & Au, 2017; Chatterjee et al., 2000; Nelson et al., 1996). Other factors studied to check their influence on loudness perception included frequency of the stimulus (Zeng & Shannon, 1994).

Studies evaluating loudness perception in those using cochlear implants have done so using loudness growth perception tests as well as intensity discrimination tests. The loudness perception tests were conducted by presenting either electrical stimuli (Anzalone & Smith, 2017; Busby & Au, 2017; Nelson et al., 1996; Steel et al., 2014) or acoustic stimuli (Kordus & Żera, 2017; Saki et al., 2015; Tak & Yathiraj, 2019a).

Zeng and Shannon (1994), to study loudness coding through electrical stimulation, evaluated eight adults using Ineraid cochlear implants and three adults using auditory brainstem implants. The participants were required to compare a standard stimulus (1000 Hz sinusoid) with five comparison stimuli (sinusoids of 100 Hz, 300 Hz, and 3000 Hz, & biphasic pulse trains of 100 Hz and 1000 Hz). The participants were asked to balance the loudness of the comparison stimuli with the standard stimulus at 10, 30, 50, 70, and 90% of the dynamic range that were chosen for each participant individually. All the electric stimuli were presented through an optically isolated constant current source. It was noted that for three comparison stimuli (3000 Hz, 300 Hz sinusoid, biphasic 1000 Hz pulse), the loudness balance function was exponential. However, logarithmic loudness balance functions were obtained for the100 Hz sinusoid and 100 Hz pulse. Thus, they concluded that loudness grows exponentially with electric stimulation at higher frequencies but at lower frequencies the loudness growth function of the electric stimulation followed a power/logarithmic function.

Based on the findings of four post-lingually deafened adults using Nucleus 22 cochlear implants, Chatterjee (1999) found that loudness was exponentially related to the amplitude of current. This outcome was established from the loudness growth functions that were measured using a 200-ms, 500-pulses/s biphasic pulses/s to variations in current amplitude and electrode separation. The participants had to judge the loudness of current presented within their dynamic range by selecting a number from 0 (don't hear) to 100 (too loud). The exponent of the loudness growth function was also noted to be linearly related to the electrode separation. It was smallest for the narrowest electrode separation and largest for the widest electrode separation.

In an extension of the earlier study done in 1999, Chatterjee et al. (2000) determined the effects of phase duration and electrode separation on loudness growth on the same four cochlear implant users evaluated earlier. The participants were evaluated using a 200 ms long train of pulses at 500 pulses/s and thresholds and dynamic range were tracked. At each electrode separation, pulses were presented using a set of amplitudes chosen from the participants' dynamic range. The participants were asked to rate the loudness of each stimulus from 1 to 100. The loudness growth curve was measured for each set of amplitudes. Similarly, the loudness growth functions were measured by presenting a number of phase durations at each electrode. It was found that for each electrode pair, the loudness growth curve was steeper for longer phase duration. Also, the loudness was found to grow exponentially with the pulse amplitude at a rate dependent on both phase duration and the electrode separation.

The steepness of loudness growth curves were noted to vary depending on the threshold at each electrode of cochlear implantees by Bierer and Nye (2014). They examined the relationship between thresholds, dynamic range, and steepness of loudness growth function in eight post-lingually deafened adults using Advanced bionics HiRes 90K implants. Initially, the channels with the lowest, medium, and highest thresholds were identified with biphasic, charge-balanced pulses having a pulse width of 102 μs at a rate of 918 pulses/second. Further, the loudness growth functions from thresholds to 10% above their most comfortable level and equal loudness contours at 50% of their dynamic range were measured for each participant. The results in both the measurements indicated that the channels with highest thresholds had narrowest dynamic range and steepest growth of loudness than the other two channels having median and lowest thresholds.

Loudness perception of 12 adolescents using unilateral Nucleus 24M cochlear implants were compared with eight normal hearing listeners by Steel et al. (2014) using electrical stimuli. For the cochlear implant listeners, the electrical pulses were delivered at the apical end of the electrode array. The normal hearing participants listened to 2 kHz tones that were delivered through insert earphones. The participants heard 11 stimulus-intensities in 10% steps ranging from -10% to 100% of their dynamic range in a random order. They were asked to rate the loudness on a visual scale, with markings representing 25%, 50%, and 75% of the maximum loudness. No significant difference in loudness perception was seen between the two groups at the level where stapedial reflex was obtained. Further, the rate of loudness growth function for the upper dynamic range (40% electrical stapedial reflex) and the lower dynamic range (threshold 40%) were not significantly different between the two groups.

In a more recent study, Busby and Au (2017) examined loudness growth at the apical, middle and basal region of cochlear implants in 30 post-lingually deafened adult using Nucleus cochlear implants. Categorical loudness scaling was measured using electrical pulses, as per the method suggested by Al-Salim et al. (2010). The dynamic range of each individual was divided into 10 equal steps that were presented in a random order. They were required to select a categorical unit that was rated from 0 to 50 in steps of 5. The results indicated that a difference occurred in the manner the maximum loudness category was perceived across electrodes and participants. For some participants the maximum loudness category was at 40 categorical units and above, whereas for others it was at and above 30 categorical units. Also, the median current levels for the same categorical units differed across electrodes and participants. However, when the electrical current levels were scaled to remove the differences in dynamic range across participants, the loudness growth was noted to be uniform across participants and electrodes. Thus, the authors concluded that there was uniform loudness across the electrodes and across the participants. Also, the loudness scaling using electrical stimulation were noted to be similar to acoustic stimulation obtained in earlier studies (Brand & Hohmann, 2001, 2002; Rasetshwane et al., 2015).

In a study similar to that of Busby and Au (2017), Kordus and Żera (2017) examined the loudness growth function of 15 post-lingually deafened, bilateral cochlear implant users (age = 36 to 67 years) using acoustic stimuli. Seven used implants from Cochlear Corporation and eight used Advanced bionics implants. The participants were tested using octave bands of noise centred at 250 Hz, 1000 Hz and 4000 Hz, presented through a loudspeaker kept at a distance of 1.65 m. The sounds were presented randomly from within their dynamic range in 5 to 10 dB steps. The participants rated the loudness of the sounds from 0 to 100. The results indicated that there was no systematic trend in the loudness growth functions. It was also noted that in those using Cochlear Corporation implants, the loudness growth function reached a plateau at 70 to 80 dB HL. In contrast, for the Advanced Bionics users the plateau was not achieved but the slope reduced. They also reported that the Cochlear Corporation implant users had loudness growth functions that were steeper below the plateau. However, the Advanced Bionics users had loudness growth functions that were two-staged, such that the function was steep from threshold to about 40 dB HL and less steep from 40 to 60 dB HL. It was noted that there was a great variability among participants and also across frequencies. The slope coefficients of the loudness functions for the Cochlear Corporation implants users were larger than that obtained by the Advanced Bionics implant users. In comparison to the coefficients obtained by the Advanced Bionics implant users, the coefficients obtained by the Cochlear Corporation implants users were more similar to the normal hearing individuals.

To study the developmental effects of loudness growth in cochlear implant users, Anzalone and Smith (2017) examined four pre-lingual and eight post-lingual deaf cochlear implant adults using Cochlear Corporation implants. Loudness growth measurement was done using 200-µs/phase biphasic pulses at a rate of 500 pulses per second through bipolar mode of stimulation. Loudness was measured as a function of current levels using amplitude magnitude estimation and magnitude production between the participants' dynamic range. For each individual it was determined whether their loudness growth curves best fitted a linear, power, exponential or forth-order polynomial model. It was found that loudness growth functions were modelled best using power functions for most of the participants. Using this power function, the loudness growth of the participants was noted to be shallower for the pre-lingually deafened group compared to the post-lingually deafened group. Also, it was observed that the linear function had a better fit for those participants who were pre-lingually deaf and the power function fitted better for those participants who were post-lingually deaf. This probably indicates that the loudness growth function varied for the pre-lingual and the post-lingual cochlear implant users.

While most studies on loudness perception in individuals using cochlear implants have evaluated loudness growth, those measuring intensity discrimination are limited. The relative intensity differential limens or the Weber fraction was evaluated as a function of stimulus level in seven post-lingual and one pre-lingual experienced adult cochlear implant user by Nelson et al. (1996). The participants used Nucleus 22 electrode devices with 1.5 mm between electrode pairs with a bipolar+1 stimulation mode. The stimuli were 500 to 300 ms biphasic pulse trains with a 200 µs pulse width, presented at a rate of 125 pulses/sec. The absolute threshold and maximum acceptable loudness level were derived for each electrode using a 500 ms pulse train. The adaptive Weber fraction was calculated for all the participants by converting dB into current step units. The psychometric functions for intensity discriminations and performance as a function of size of intensity change were evaluated. It was found that the Weber fraction improved systematically with stimulus intensity and were not systematically different across electrodes. There was no difference seen in prelingual and post-lingual cochlear implant users. It was concluded that the sensitivity to intensity change was better for acoustic stimulation when compared to electrical stimuli. This conclusion was made based on earlier studies done using acoustical stimuli by Jesteadt et al. (1977) and Schroder et al. (1994). It was observed that the Weber fraction was poor at low intensities but improved across the dynamic range. The number of discriminable intensity steps across the dynamic range varied among individuals depending on their dynamic range, overall sensitivity and rate of improvement of the Weber fraction with stimulus level.

More recently, Saki et al. (2015) evaluated loudness perception by comparing the intensity difference limen for nine post-lingual Advanced bionics cochlear implant users (mean age = 31.77±6.6 years) with 17 normal hearing individuals (mean age = 32.76±6.5 years). Intensity difference limen was measured using pure-tones having frequencies of 500 Hz, 1000 Hz, 2000 Hz, and 4000 Hz in a sound field setup. A significant difference was noted between the two groups at all frequencies. Further, responses obtained after providing the cochlear implant users eight sessions of training resulted in a significant improvement in the intensity difference limen.

In a similar study, intensity discrimination thresholds were compared between 15 children with congenital hearing loss who used monaural cochlear implants (aged 6 to 15 years) and 15 age matched typically developing children by Tak and Yathiraj (2019a). Responses were obtained for three warble-tones (500 Hz, 1000 Hz, & 4000 Hz) and three vowels (/a/, /i/, & /u/) that were presented at 50 dB HL through a loud-speaker, using a three-alternative force-choice method. It was noted that the children using cochlear implants had significantly poorer thresholds than the typically developing children for some stimuli (4000 Hz warble-tone, & vowels /u/ and /a/) and not for others (500 Hz, 1000 Hz warble-tones, & vowel /i/).

In a subsequent study, Tak and Yathiraj (2021) assessed relative loudness judgement of 20 children using cochlear implants aged 6 to 14 years and 20 age matched typically developing children. Relative loudness judgement was measured using a two-alternative forced choice method where the participants had to select between two pictures representing sounds that occur in day-to-day situations. This was done for 30 stimuli. It was noted that significant difference in relative loudness judgment scores occurred between the children using cochlear implants and the typically developing children.

It can be surmised from the review on loudness perception in those using cochlear implants that the steepness of the slope the loudness growth function was found to depend on the electric dynamic range, electrode separation, phase duration, thresholds and also the frequency of the stimulus. Further, the loudness growth functions differed across different manufacturers as well as across participants. For electrical stimulation, pre-lingual implant users were found to have a linear loudness growth function, while a power function was noted for post-lingual implant users. It was also observed that differential limen for intensity varied across the dynamic range of individuals, with it being poorer at lower intensities, and better at higher intensities. For acoustical stimuli, the differential limen was noted to be worse for cochlear implant users than normal hearing individuals.

2.4 Loudness Perception in Individuals using Hearing Aids

Evaluation of loudness perception is considered an important step while fitting hearing aids. It is reported to ensure satisfactory acceptance of devices by users (Blamey & Martin, 2009; Shi et al., 2007). The perception of loudness was noted to vary depending whether the individuals with hearing loss used linear and non-linear hearing aids (Jenstad et al., 2000; Kam & Wong, 1999; Shi et al., 2007). Hence, studies have been conducted to evaluate how settings in hearing aids effect loudness perception (Gottermeier & De Filippo, 2018; Jenstad et al., 2000; Scollie et al., 2010). Besides studying the impact of hearing aid settings on loudness growth, intensity discrimination tasks have also been evaluated (Devi et al., 2017; Musa-Shufani et al., 2006; Philibert et al., 2002; Robinson & Gatehouse, 1995; Whitmer & Akeroyd, 2011).

In 1999, Olsen et al. noted that consistent use of hearing aids by listeners with hearing loss changed their perception of loudness. The authors examined loudness growth perception of 36 adults with acquired moderately-severe sensorineural hearing loss. Eighteen of these participants (aged 24 to 64 years) used hearing aids and 18 (aged 42 to 65 years) did not use hearing aids. The loudness perception was examined for all participants using a categorical loudness scaling test while not wearing their hearing aids. They were tested using a random order presentation utilising three pure-tone (500 Hz, 1000 Hz, 2000 Hz, & 4000 Hz). They heard the stimuli through earphones at intensities that ranged from threshold minus 5 dB to the most tolerable level and rated the loudness on a seven-point rating scale. It was noted that most of the participants who used hearing aids did not choose the ‘very loud’ and ‘too loud’ categories. Also, they assigned the categories ‘loud’ and ‘very loud’ at a significantly higher levels than the non-users.

The effect of liner amplification and wide dynamic compression (WDRC) on loudness appropriateness was evaluated by Kam and Wong (1999) on 20 adults (16 to 70 years) with moderate to moderately-severe flat sensorineural hearing loss. Speech intelligibility was measured using monosyllables in quite at three presentation levels (50 dB, 65 dB, & 80 dB SPL) and in the presence of spectrally shaped noise at +6 dB SNR at a presentation level of 65 dB SPL. Most of the participants found the loudness to be appropriate with the WDRC program at 50 and 80 dB SPL compared to the linear setting.

Jenstad et al. (2000) compared audibility, loudness rating, and comfortability through linear and WDRC hearing aids in 10 participants aged 10 to 27 years having bilateral moderate to severe sensorineural hearing loss. They were compared with 12 normal hearing individuals aged 21 to 34 years. The single channel WDRC fitting had a compression threshold of 45 dB, 10 msec attack time and 200 msec release time. The normal hearing individuals were tested monaurally without any hearing aid. Loudness perception was measured for 20 presentation levels using a 9-point categorical rating scale (not hear, very soft, soft, slightly soft, comfortable, slightly loud, loud, very loud, & uncomfortable) for frequency-modulated tones, environmental sounds and speech. The dynamic range with WDRC was found to approximant that of the normal hearing group more than the dynamic range of the linear hearing aids. Further, the loudness growth function with the WDRC was better normalized than that of the loudness growth functions obtained with the linear fitting. For the 1000 Hz and 2000 Hz warble-tones, the WDRC goodness-of-fit line was almost identical to the normal curve. However, for the 4000 Hz, speech and environmental sounds, the goodness-of-fit lines were almost parallel to the normal lines with the same slope but separated by a constant. This difference in the two curves corresponded to the difference in the actual gain provided by the instrument.

To study the perception of loudness with compression hearing aids, Shi et al. (2007) evaluated 10 normal hearing individuals (19 to 25 years) and 12 individuals with mild to severe hearing impairment (66 to 84 years). Those with hearing impairment used WDRC hearing aids with a compression ratio of ≥ 1.3:1. Warble-tones (500 Hz & 2000 Hz) were presented through a loudspeaker at 4, 10, 20, 30, 40, 50, 60, and 70 dB SL for the normal hearing individuals and at 3, 5, 8, 10, 15, 20, 25, 30, and 35 dB SL in both aided and unaided conditions for those with hearing impairment. Loudness growth was estimated using absolute magnitude estimation method by asking the participants to assign a number corresponding to the loudness of the stimuli. Additionally, those with hearing impairment were evaluated using the ‘Profile for Aided Loudness’ that consisted of two rating scales, one that evaluated loudness rating (0 to 7) and another that evaluated satisfaction rating (1 to 5). In a few subjects the loudness growth was shallow compared to the normal loudness growth curve, implying that the hearing aids were ‘over compressing’. In others it was steep, implying that it was ‘under compressing’. The average loudness rating for those wearing hearing aids was similar to that of the normal hearing individuals at high levels. It was also reported that all listeners rated soft level sounds to be higher than that of the target, but this was not significantly different from that of the normally hearing individuals. They attribute the over and under compression to effective compression ratio.

Scollie et al. (2010) compared WDRC hearing aids, programmed based on DSL[i/o] and NAL-NL1, using loudness ratings of 24 children and 21 adolescents (6 to 20 years) having mild to moderately-severe sensorineural hearing loss. The participants were given trials with both DSL[i/o] and NAL-NL1. Aided loudness rating was assessed before and after each trial using the rainbow passage presented at random presentation levels ranging from 55 dB SPL to 80 dB SPL in 5 dB steps. The participants were instructed to rate loudness on a 7-point rating scale by pointing to a verbal descriptor provided along with line-drawings of facial expression. The results indicated that at the time of fitting there was a significant difference between the loudness rating through the two prescription methods. However, after home trials there were no significant difference between the two prescriptions, except for the few mid-levels in some participants. Normal hearing young adults rated the loudness to be higher at low intensity levels than those with hearing loss wearing hearing aids programmed with either prescriptive formula. However, at mid and high levels the difference was not significant.

Aided loudness growth perception was determined by Gottermeier and De Filippo (2018) in adults with severe to profound hearing loss. Twenty-three bilateral hearing aid users, who wore their devices for at least 3 years, rated the loudness growth on an eight-point rating scale. Loudness growth perception was tested using 500 Hz, 1000 Hz and 2000 Hz warble-tones that were presented in an ascending order in a free-field setup. The responses of the hearing aid users were compared with that of 15 adults having normal hearing. Loudness growth curves were fitted to a linear function after excluding the responses near the threshold and loudness discomfort levels. When the loudness growth function of adults with hearing loss were plotted against the functions of the normal hearing listeners, four different patterns of loudness growth curve were noted, which were described as steep, shifted right, hypersensitive and shallow. It was noted that the participants using hearing aids needed higher intensity to perceive sounds equally loud as the normal hearing individuals. Also, most of the participants with hearing loss responded in a similar manner as the normal hearing listeners beyond the comfort region of loudness growth.

Similar to what was seen with cochlear implant users, studies have also evaluated intensity discrimination of those using hearing aids. Robinson and Gatehouse (1995) evaluated intensity discrimination in four participants with hearing loss (aged 54 to 82 years) who were long term users of linear hearing aids and five normal hearing participants (aged 18 to 35 years). Intensity discrimination was measured through earphones using a bandlimited harmonic tone complexes with a spectral shaping functions centred at 250 Hz and 3000 Hz. For the normal hearing participants, the minimum and maximum standard levels were 10 dB SPL and 90 dB SPL, respectively. However, for participants with hearing impairment who were tested without hearing aids, the minimum standard level was the lowest level at which the standard deviation of each threshold was less than 3 dB. The maximum level was 100 dB SPL. A three-alternative forced choice method, where participants had to choose the interval with loudest level, was used to obtain the responses. It was observed that at 250 Hz, no difference was noted in the Weber function between the aided and unaided ears. However, at 3000 Hz for lower presentation levels, the unaided ear was found to be more sensitive than the aided ear. At intensity levels greater than 85 dB SPL, the aided ear was found to be more sensitive. Also, the sensitivity of normal hearing participants was better than those with hearing loss.

In contrast to the findings of Robinson and Gatehouse (1995), Philibert et al. (2002) noted that intensity discrimination thresholds were greater for non-users than long-term hearing aid users when tested at 75 dB SPL as well as 95 dB SPL. The intensity discrimination was measured on nine long-term hearing aid users (64 to 82 years) and nine non-users (73 to 90 years). The testing was conducted through headphones using pure-tones of 500 Hz and 2000 Hz with standard intensity levels of 75 dB SPL and 95 dB SPL. The non-users were found to have greater intensity discrimination thresholds compared to the long-term hearing aid users. At low intensity, the discrimination threshold was noted to be greater than at high intensity. Also, the thresholds were greater at the lower frequency than at the higher frequency.

Musa-Shufani et al. (2006) studied the effect of compression on intensity difference, important for directional hearing in a horizontal plane. Five normal hearing adults (25 to 45 years) and seven participants with symmetrical sensorineural hearing loss (48 to 64 years) were evaluated. Narrow-band filtered noise, centred at 500 Hz and 4000 Hz and processed to have compression ratios of 1:1, 3:1, and 8:1 through a programmable digital signal processor, were presented through headphones worn by the participants. The testing commenced at a comfortable level. Using a staircase method, the just noticeable difference in intensity level was obtained. The participants responded by indicating whether the stimulus originated from left or right of the midline using a two-alternative forced choice method. With increase in compression ratio, the just noticeable difference was noted to increase for both the frequencies. Also, in comparison to the normal hearing participants, the just noticeable differences were higher for those with hearing impairment.

The effect of amplification on intensity level discrimination was assessed using speech stimuli by Whitmer and Akeroyd (2011). The intensity discrimination thresholds were evaluated on 38 participants using hearing aids (31 fitted with bilateral hearing aids, & 7 fitted with monaural hearing aids) and eight participants with normal hearing. The compression ratio of most hearing aids was between 1.2 and 2:1. Both aided and unaided intensity discrimination were measured in those using hearing aids with three types of speech stimuli (stationary speech-shaped noise, single-syllable male-talker words, & male-talker sentences). The pedestal level roved across trials from 65 to 70 dB in 0.5 dB increments. The intensity discrimination thresholds were evaluated through loudspeaker kept at 0° azimuth using a two-alternative forced choice method. It was noticed that there was no difference in level discrimination when aided and unaided conditions were compared and hence, a clear effect of compression on intensity discrimination was not observed. Also, the aided thresholds were highest for words, followed by sentences, and lowest for noise. For noise, the thresholds were significantly higher for participants with hearing loss in the aided as well as the unaided condition than the normal hearing participants. However, words thresholds for those with hearing loss were higher only in the aided condition when compared with the normal hearing participants.

Devi et al. (2017) evaluated difference limen for intensity of 20 ears of adults without and with WDRC hearing aids. The adults, aged 18 to 55 years with moderate sensorineural hearing loss, were tested using 750 Hz and 1500 Hz pure-tones. The stimuli were presented at 20 dB SL through loudspeakers and the intensity discrimination thresholds were compared without and with the hearing aid. Using a 3-alternative forced choice method, the participants were asked to indicate the interval having a difference in loudness. It was noted that with the hearing aids the intensity discrimination thresholds were greater than without hearing aids. This was ascribed to the deterioration of intensity discrimination thresholds due to the compression feature in hearing aids. Also, it was noted that there was no significant difference in thresholds between the two stimulus frequencies.

Thus, from the review it can be observed that most hearing aids users can perceive loudness growth using compression hearing aids. However, the loudness growth differed from that seen in normal hearing individuals. At low intensity levels most of the participants rated loudness to be lesser compared to normal hearing individual. However, at higher intensity levels they perceive the loudness of the stimuli similar to normal hearing listeners. Only a few studies reported of individuals having difficulty in loudness perception even with the use of compression hearing aids. Variations the in the way participants using hearing aids perceive loudness growth was attributed to compression used in hearing aids. Intensity discrimination was also found to be different in those using hearing aids. The use of compression in hearing aids was observed to affect intensity discrimination.

From the overall review it can be noted that loudness perception in normal hearing individuals was dependent on various stimulus related factors such as intensity, frequency, duration and bandwidth. Further, among these individuals, the order of stimulus presentation was also noted to affect loudness perception. Additionally, participant related factors such as age of the listener and their hearing acuity were also noted to have an impact on loudness perception. The use of listening devices such as cochlear implant and hearing aids did not result in loudness perception becoming similar as normal hearing individuals. Great variability was observed in loudness perception among those using cochlear implants and also for those using hearing aids. Loudness perception of those using cochlear implants was mainly done on adults using electrical stimuli. Relatively few studies used acoustical stimuli to study loudness perception in them.

3. Methods

The method was designed to evaluate loudness growth identification and intensity discrimination in typically developing children, children using cochlear implants and children using hearing aids. The study was conducted using a standard group comparison design. The sample size was calculated using G*Power Version 3.1.9.2 (Faul et al., 2007) with an error probability of 0.05 and power of 0.8. The sample size for each participant group was calculated based on the mean and standard deviation given by Gottermeier and De Filippo (2018) that had an effect size of 0.79. The recommended sample size was 32 for the typically developing children and 22 for the clinical group.

3.1 Participants

Using a purposive sampling technique, three groups of participants were selected, consisting of 31 typically developing children, 25 children using a cochlear implant, and 20 children using hearing aids. While the typically developing children were selected from regular schools located in Mysuru, the clinical groups were selected from the clinics of the All India Institute of Speech and Hearing, Mysuru, nearby special oral schools and regular schools.

The typically developing children were aged 6 to 15 years (mean age = 10.16 years; SD = 2.57), while the children using monaural cochlear implants (19 Cochlear Nucleus, 2 Advanced bionics, 2 Digisonic, & 2 MedEl) were aged 6 to 15 years (mean = 10.50; SD = 3.40). The other clinical group initially included 23 children using hearing aids, three of whom dropped out of the study midway. The remaining 20 children were aged 6 to 15 years (mean age = 9.40 years; SD = 3.30). The demographic details of the children using cochlear implants and children using hearing aids are given in Table 3.1 and Table 3.2, respectively. Each of the participant groups met the below given inclusion criteria.

3.1.1 Inclusion Criteria for the Typically Developing Children

The typically developing children were required to have the following:

- Bilateral air conduction and bone conduction pure-tone thresholds less than 15 dB HL from 250 Hz to 8 kHz and 250 Hz to 4000 Hz, respectively, indicating the presences of normal hearing (Goodman, 1965),
- No middle ear pathology, confirmed by the presence of A-type tympanograms and ipsilateral and contralateral acoustic reflexes,
- No history of any speech, language, and hearing problems,
- Average intelligence, as per the Coloured Raven's Progressive Matrices (Raven, 1952),
- No illness on the day of evaluation.

3.1.2 Inclusion Criteria for the Children Using Cochlear Implants

The children using cochlear implants had the following inclusion criteria:

- Severe to profound hearing loss and met the criteria for cochlear implants, as recommended by Wolfe (2018),
- No middle ear problems, indicated by the presence of A-type tympanograms,
- Used unilateral cochlear implant,
- Used cochlear implants for at least one year and had stable maps,
- Aided warble-tone thresholds within the speech spectrum from 250 Hz to 8000 Hz,
- Language age of at least 5 years, based on routine speech-language evaluations carried out by qualified speech language pathologists,
- Communicated using speech regularly,
- Average intelligence, based on the responses on the Coloured Raven's Progressive Matrices (Raven, 1952),

- No illness on the day of evaluation.

3.1.3 Inclusion Criteria for the Children Using Hearing Aids

The children using hearing aids had the following criteria:

- Bilateral hearing loss with moderate to severe sensorineural hearing loss, as classified by Goodman (1965), in at least one ear,
- Flat configuration, as described by Pittman and Stelmachowicz (2003) in both ears,
- A-type tympanograms, indicating no middle ear problems,
- Fitted with binaural digital behind-the-ear hearing aids for at least 1 year,
- Aided warble-tone thresholds within the speech spectrum from 250 Hz to 4000 Hz,
- Language age of at least 5 years, based on routine speech-language evaluations carried out by a qualified speech language pathologist,
- Communicated using speech,
- Average intelligence as measured by the Coloured Raven's Progressive Matrices (Raven, 1952),
- No illness on the day of evaluation.

3.2 Instrumentation

The below mentioned equipment were used to carry out the study:

- Motu MicroBook IIc USB 2.0 external card interface and a Behringer B-2 Pro dual diaphragm condenser microphone was used to record the speech stimuli on a laptop (HP Envy, with Intel Core i7-6500U processor & 8.00 GB RAM). The laptop was utilized to develop and play the recorded stimuli for intensity discrimination and loudness growth identification.

- A calibrated dual channel diagnostic audiometer (Maico MA 52) with Maico HB-7 headphones, B-71 bone vibrator, and a dB technologies M160 loudspeaker was used to select the participants and present / route the test material,
- A calibrated middle ear analyser (Interacoustics Titan) was utilized to perform tympanometry and reflexometry, to rule out the presence of a middle ear problem.
- Two digital BTE hearing aids (Audio Service HP4 G3), suitable for those with moderate to severe hearing loss, were chosen as ‘test hearing aids’ to evaluate all the participants. These hearing aids were selected as they had the option to load multiple programs, as well as the provision to vary the compression ratio and compression kneepoint.
- Fonix 8000 hearing aid analyser was used to verify the compression parameters of the ‘test hearing aids’.
- The hearing aid users were also evaluated with their own binaural hearing aids, prescribed by qualified audiologists.
- The cochlear implant users were assessed with them wearing their unilateral device in the prescribed settings.

All equipment that required calibration were calibrated regularly throughout the process of data collection. The calibration for the audiometer was done as per the guidelines of American National Standards Institute (2004), once in 3 months. The middle ear analyser was calibrated regularly, based on the guidelines provided by American National Standards Institute (R2012), and the hearing aid analyser was calibrated using the guidelines provided by ANSI (2014).

Table 3.1

Demographic details of participants using cochlear implants

Sl. No.	Age (years) / Gender	Implant	Processor	Parameter	Prior Experience with HA (years)	Age of implantat-ion (years)	Implanted ear	Experience with implant (years)	Average aided threshold
1	6 / M	Freedom contour advance	CP810	ADRO+ ASC	0.5	2	R	4	25.00
2	12 / M	Freedom	Freedom	ADRO+ ASC	1	6	R	6	28.33
3	15 / M	Freedom	Freedom	ADRO+ ASC	7	8	L	7	28.33
4	11 / M	CI 512	CP810	ADRO+ ASC	2.5	4	L	7	16.67
5	11 / M	Freedom contour advance	CI24RE	ADRO+ ASC	3	5	R	6	21.67
6	8 / F	CI 24 RE	CP802	ADRO+ ASC	0.5	4	R	4	23.33
7	8 / M	Freedom	Freedom	ADRO	0.5	2	L	6	15.00
8	8 / M	CI 422	CP910	Scan	3	5	R	4	26.67
9	14 / F	Nucleus 24 (R)	CP810	ADRO+ ASC		5	L	9	23.33
10	8 / F	CI 24 RE	CP802	ADRO+ ASC	3	5	R	3	26.67
11	13 / F	CI 24 RE	CP802	ADRO+ ASC	2	3	L	9	21.67
12	13 / F	CI 512	CP810	ADRO+ ASC	5	6	L	7	26.67
13	11 / F	CI 512	CP810	ADRO+ ASC	1	3	R	8	23.33
14	7 / F	Nucleus 24RE	CP802	ADRO+ ASC	2	3	L	4	18.33
15	9 / F	Freedom	CP810	ADRO+ ASC	2.5	5	R	4	20.00
16	15 / M	Freedom	CP910	ADRO	3	6	R	9	18.33
17	12 / F	Nucleus 24®	CP810	ADRO+ ASC	0.5	3	L	9	25.00
18	16 / F	Nucleus 24	Sprint	ADRO	5	6	R	10	26.67
19	12 / M	Freedom	CP810	ADRO + ASC	0	6	L	6	23.33
20	7 / F	HiRes90k	Neptune	Clear voice medium	4	5	L	2	21.67
21	11 / F	HiRes90k	Auria BTE	-	8	5	R	6	28.75
22	8 / M	Digisonic	Saphyr SP	Voice track low	4	5	R	3	23.33

23	8 / M	Digisonic SP	Saphyr SP	Voice track low	3	6	R	2	28.33
24	15 / M	MedEl	Opus 2 Power	NA	2	3	R	12	20.00
25	10 / M	MedEl Pulsar CI 100	Opus 2 Power	NA	2 months	2	R	8	30.00

Note. R = Right ear; L = Left ear; M = Male; F = Female; HA = Hearing Aid; CI = Cochlear implant; NA = Not available

Table 3.2

Demographic details of participants using hearing aids

Sl. No.	Age (Years)	Listening Age (Years)	Gender	Ear	Average unaided threshold	Average aided threshold	Hearing devices
1	11	8	F	R	81.67	37.50	Widex M-219
				L	81.67	37.50	Widex M-219
2	11	6	M	R	73.33	38.75	Siemens Prompt P
				L	48.33	38.75	Aries Pro
3	14	11	M	R	60.00	38.75	Danavox Logar 598
				L	71.67	36.25	Danavox Logar 599
4	5.5	1.5	M	R	73.33	32.50	Danavox Logar 598
				L	73.33	32.50	Danavox Logar 598
5	13	4	F	R	78.33	43.75	Riva 2HP
				L	81.67	40.00	Riva 2HP
6	10	3	M	R	45.00	20.00	Widex UPS
				L	45.00	25.00	Widex UPS
7	13	1	F	R	60.00	28.75	Oticon Riva Pro Mini
				L	41.67	27.50	Oticon Riva Pro Mini
8	10	7	F	R	90.00	35.00	Siemens Lotus Pro SP
				L	85.00	33.75	Siemens Lotus Pro SP
9	6	4.5	M	R	75.00	43.75	Phonak Naida
				L	78.33	47.50	Phonak Naida
10	6	4	M	R	70.00	32.50	Phonak Una SP
				L	70.00	28.75	Phonak Una SP
11	6	2	M	R	58.33	37.50	Oticon Get P
				L	56.67	31.25	Oticon Get P
12	9	5	F	R	58.33	38.75	Riva 2HP
				L	63.33	35.00	Riva 2HP
13	15	13	M	R	78.33	37.50	Siemens CIELO 2P
				L	81.67	43.75	Siemens CIELO 2P
14	6	2	M	R	93.33	46.25	Starkey ignite 20
				L	88.33	42.50	Starkey ignite 20

15	5.5	2.5	F	R	65.00	47.50	Siemens Lotus Pro SP
				L	106.67	70.00	Siemens Lotus Pro SP
16	6	1.5	F	R	83.33	46.25	Phonak Naida V-50 UP
				L	73.33	40.00	Phonak Naida V-50 UP
17	6	1.5	M	R	81.67	20.00	Danavox Logar 598
				L	83.33	23.75	Danavox Logar 598
18	9	3	M	R	70.85	36.25	Riva 2HP
				L	70.85	38.75	Riva 2HP
19	15	7	F	R	78.33	28.75	Bernofon win 112
				L	75	28.75	Bernofon win 112
20	11	7	F	R	83.33	42.50	Riva 2HP
				L	86.67	42.50	Riva 2HP

Note. R = Right ear; L = Left ear; M = Male; F = Female

3.3 Test environment

The audiological tests were conducted in a sound treated two-room suite. The maximum permissible ambient noise level was as specified by ANSI/ASA (1999). The room was also adequately lit and free from distractions. The non-audiological tests were conducted in quiet, well-lit rooms, free from distractions.

3.4 Material

Loudness perception was assessed using non-verbal and speech stimuli. Three warble-tones (500 Hz, 1000 Hz, & 4000 Hz) and three vowels (/u/, /a/, & /i/) were selected to represent low, mid, and high frequencies. A 250 Hz warble-tone was utilized for practice.

To obtain the loudness growth identification responses, a chart representing a six-point loudness level scale was developed. For assessing intensity discrimination, scripts were written using a software (Psycon, Version 2.18) loaded in a laptop. Details of the development of the above material are described further.

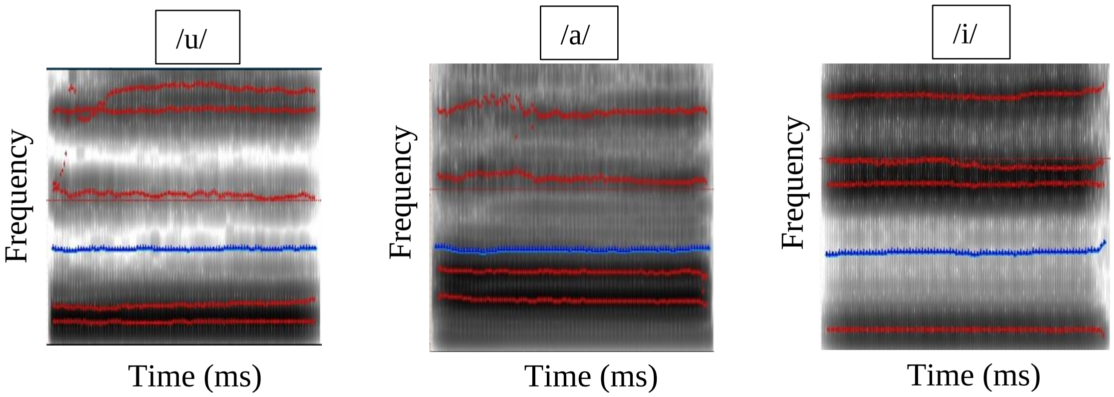
3.4.1 Development of the Loudness Growth Identification test

The three warble-tones, used as non-verbal material, were generated from an audiometer. The warble-tones had a frequency deviation of 5% and repetition rate of 5 Hz. The three vowels selected for the study were audio recorded using a condenser microphone (Behringer B-2 Pro dual-diaphragm), kept at a distance of 12 cm from the mouth of a female speaker having a neutral Indian accent. The microphone was connected to an HP Envy laptop with an Intel Core i7 processor via a Motu MicroBook IIc USB 2.0 extern sound card interphase. Adobe Audition (version 3.0) software, loaded on the laptop, was used to record the vowels at a sampling rate of 44100 Hz and 32 bits resolution. The stimuli were scaled such that the three vowels had similar average RMS power. A 1 kHz calibration tone having a duration of 1000 ms was inserted at the beginning of the recorded vowels.

To check the clarity of the recording, the vowels were played to 10 adults who had normal speech and hearing abilities. All 10 adults rated the speech as being clear and were able to correctly identify them. The spectrogram of the vowels (/u/, /a/ & /i/) used for the study are depicted in Figure 3.1.

Figure 3.1

Spectrograms of the vowels /u/, /a/, and /i/, with the red line representing the formant frequencies and the blue line representing the fundamental frequency.



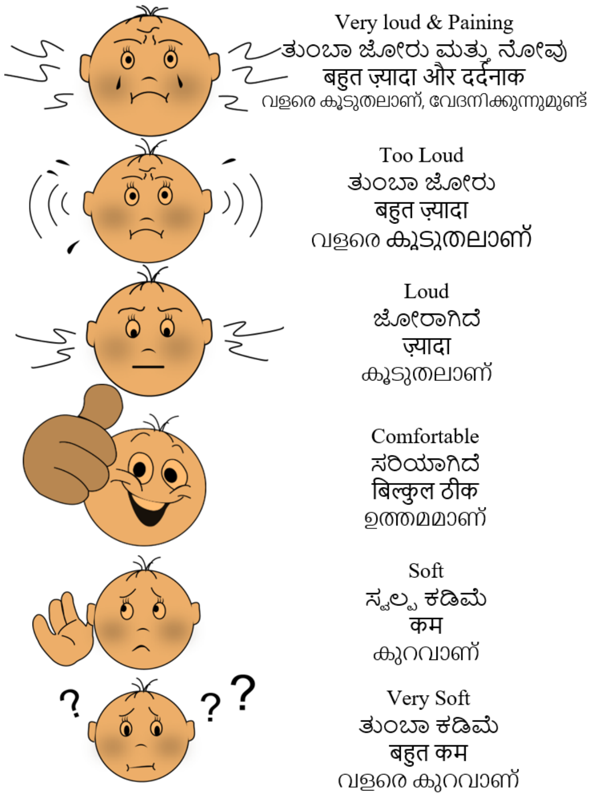
To obtain the responses of the participants for the loudness growth identification test, a loudness growth chart was developed in line with that developed by Kawell et al. (1988). Instead of the five-point scale (very soft, just right, a little bit loud, too loud & hurts) developed by Kawell et al. (1988), a six-point rating (very soft, soft, comfortable, loud, too loud, & very loud and paining) was developed with the terminology changed. These changes were made based on the feedback given by 10 experienced speech and hearing professionals working with children using hearing devices.

The English words used to label the six loudness levels were translated to Kannada, Hindi and Malayalam. This was done so that children with knowledge of these different language could be studied, in case they could read. The translation was done by normal hearing adults who were native speakers of the language and were fluent speakers of Indian-English. The translated terms of each language were further verified by at least two speech and hearing professionals who were native speaker of the language and worked with children using listening devices. The modifications suggested by the professionals were incorporated.

To depict the six loudness levels pictorially, three professional artists were asked to provide graphic designs. These designs were shown to 10 speech and hearing professionals who had experience in evaluating loudness perception in children with hearing impairment. They were asked to select the chart that had the least ambiguous pictures and were attractive. They were also encouraged to suggest any modifications, if required. The chart selected by 80% of the professionals was chosen and the suggested modifications were incorporated. One of the modifications suggested was to have multiple charts to hold the attention of the children. Hence, four additional charts were prepared with the same pictures represented in different colours. The modified loudness level chart (Figure 3.2) was field tried on three typically developing children aged 6 to 7 years. As all the children were able to comprehend that each of the six pictures in the chart represented different levels of loudness, no further modifications were made.

Figure 3.2

Sample of one of the loudness growth charts



3.4.2 Generation of Material for Intensity Discrimination test

For the intensity discrimination test, material similar to that used for the loudness growth identification test were utilised. However, the warble-tones were generated using the Aux scripts (Script 1 & Script 2) provided by Kwon (2012), having acoustical parameters identical to that generated by the audiometer for the loudness growth identification test.

Script 1 was used to generate the anchor tone, and script 2 was used to generate the variable tone.

db(a)*ramp(fm (freq1, freq2, mod_rate, time_marker),ramp duration) -------- Script 1

db(a+v)*ramp(fm (freq1, freq2, mod_rate, time_marker),ramp duration) ----- Script 2

where ‘freq1’ and ‘freq2’ indicates the cut-off frequencies with a frequency deviation of 5% from the centre frequency; ‘mod_rate’ indicates the rate of modulation; ‘time_marker’ represents the duration of the signal, which was maintained at 1000 ms; db(a) indicates the intensity of the anchor, which was equivalent to 50 dB HL at the patients’ ear level; and ‘v’ indicates the intensity level above the anchor tone level. The ramp duration for the signal was maintained at 10 ms. This Aux script was run through Psycon (Version 2.18).

The audio recorded vowels wave files, which were also used for the loudness growth identification test, were presented through the Psycon software. Script 3 and 4 were used to play the wave files, with the former used to play the anchor stimulus and the latter used to play the variable signal.

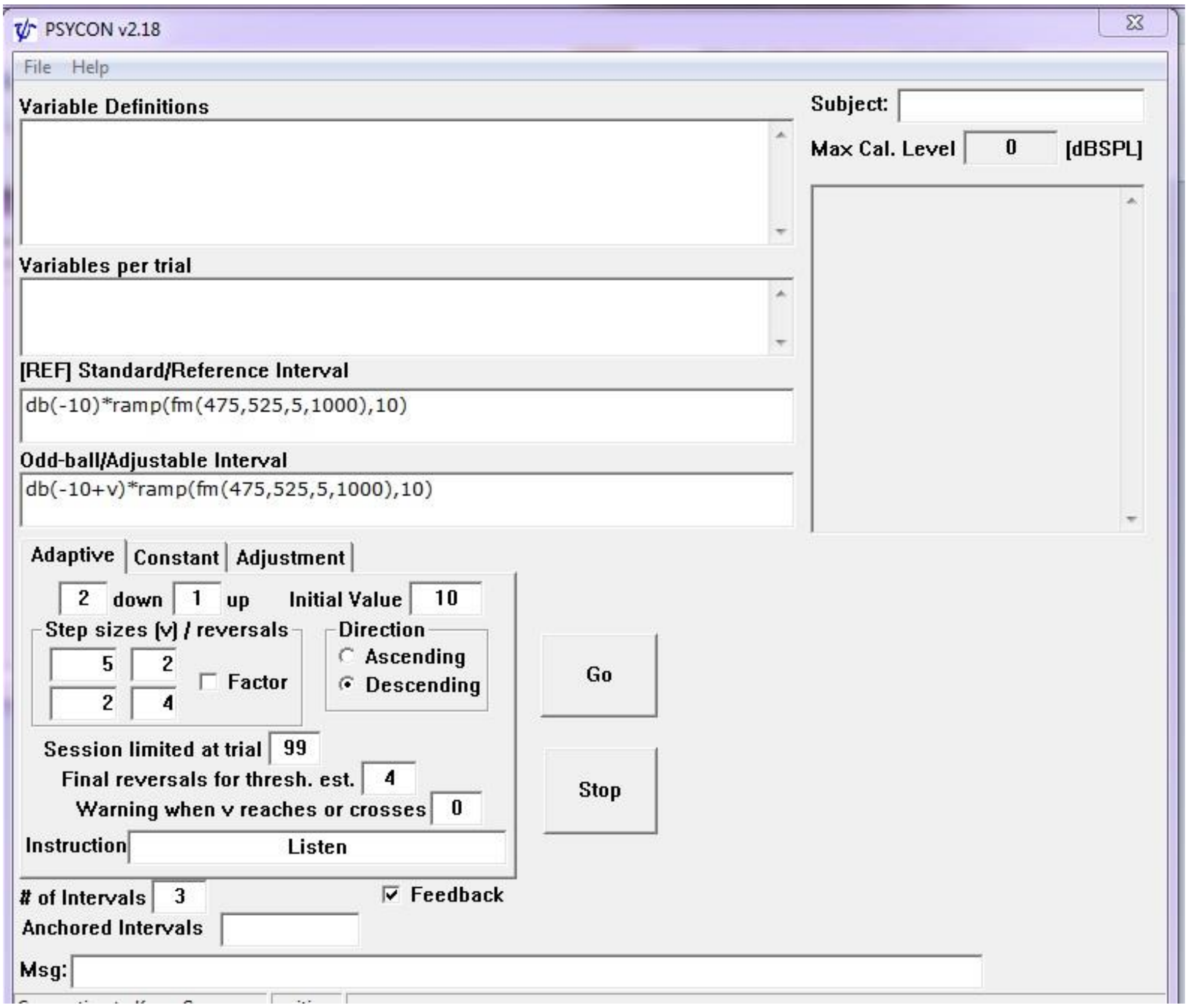
rms(wave (wave_name), a) ---------------- Script 3

rms(wave (wave_name), a+v) ---------------- Script 4

where, wave_name is the path to read the recorded wave file. The rms value (a) was set in such a way that the intensity of the anchor stimulus was equivalent to 50 dB HL. Further, in the Psycon software, the parameters were set so that the responses could be obtained using a three-interval forced choice method with an inter-stimulus interval of 400 ms. The other parameters that were set in the software are given in the screenshot provided below (Figure 3.3).

Figure 3.3

Screenshot of the settings used in the Psycon software (Version 2.18) for assessing intensity discrimination.



Variable Definitions

Variables per trial

Subject:

Max Cal. Level 0 [dBSPL]

[REF] Standard/Reference Interval
db(-10)*ramp(fm(475,525,5,1000),10)

Odd-ball/Adjustable Interval
db(-10+v)*ramp(fm(475,525,5,1000),10)

2 down 1 up Initial Value 10

Step sizes (v) / reversals
5 2
2 4
☐ Factor

Direction
○ Ascending
● Descending

Session limited at trial 99
Final reversals for thresh. est. 4
Warning when v reaches or crosses 0
Instruction Listen

# of Intervals 3
☑ Feedback
Anchored Intervals
Msg:

3.5 Procedure

Ethical clearance from the institutional ethics committee (Appendix 1) and written consent were obtained from the parents or caregivers of the children before conducting the study. The procedure followed was in accordance with the ‘Ethical guidelines for Bio-behavioural research involving human subjects’ (2009) of the institute.

Initially, the participants were evaluated to ensure if they met the inclusion criteria. Those who were selected were subjected to further evaluation to establish their loudness growth identification and intensity discrimination for the six different stimuli (three vowels & three warble-tones). The children using cochlear implants as well as those using hearing aids were tested with them wearing their own devices. Additionally, the latter group was also evaluated using binaural 'test hearing aids'.

3.5.1 Procedure for Selection of Participants

To ensure that the children met the inclusion criteria, relevant information was obtained from their parents / caregivers as well as they were subjected to several tests.

A case history was obtained for each participant from a parent / caregiver who was familiar with the child, using an interview technique. The information gathered varied depending on whether the child was a part of the control group or the clinical group. For all children, information was obtained regarding their general medical status, auditory abilities, and the presence of additional disabilities. For children with a hearing loss, details were obtained regarding the hearing device used, which included information about the style and model; duration of use of the device; number of times the device was changed; regularity in the use of the device; and any other relevant issues. Additionally, information was obtained about the mode of communication used by the children.

Pure-tone audiometry was conducted to determine the hearing status of the children. Air-conduction thresholds from 250 Hz to 8000 Hz and bone-conduction thresholds from 250 Hz to 4000 Hz were measured using a modified Hughson Westlake method (Carhart & Jerger, 1959). Based on the classification provided by Goodman (1965), the degree of hearing loss was noted.

Middle ear functioning was evaluated using tympanometry and acoustic reflexes. Tympanograms were obtained bilaterally for all children for a 226 Hz probe frequency presented at 85 dB SPL. The presence of ipsilateral and contralateral acoustic reflexes was checked in each ear of the typically developing children at 500 Hz, 1000 Hz, 2000 Hz and 4000 Hz. Children with hearing impairment were evaluated to confirm that they had A-type tympanograms.

Aided audiometry was done on those children who used hearing aids and cochlear implants at octave and mid octave frequencies from 250 Hz to 8000 Hz using warble-tones. Only those children who had aided thresholds from 250 Hz to 4000 Hz that were within the speech spectrum were included for subsequent evaluations.

Speech and language skills of the children was measured by a qualified speech language pathologist, using the 'Receptive and expressive language test' (Bzoch, League, & Brown 2003). Those children with a receptive age greater than 5 years were included in the study.

Intelligence was evaluated using Raven's Coloured Progressive Matrices (Raven, 1952). Children who had an intelligence quotient of less than 90 were excluded from the study.

3.5.2 Procedure to Evaluate Loudness Perception

Loudness perception of the three participant groups (typically developing children, children using cochlear implants, & children using hearing aids) was done using two different tests. While one evaluated *loudness growth identification,* the other measured *intensity discrimination*. All three groups of participants underwent both loudness perception tests, however the number of times they were evaluated varied depending on whether they wore a hearing device or not, as well as depending on the type of device worn by them. The typically developing children and the children using cochlear implants were tested only once. However, the children using hearing aids were tested thrice, once with their own binaural hearing aids, and twice with a pair of binaural 'test hearing aids' programmed to have two different setting, one being linear and the other being non-linear.

In all three groups of participants, the order in which the two loudness perception tests were presented was randomized. Half the children were evaluated with the 'loudness growth identification test' first and the other half were first evaluated with the 'intensity discrimination test'. This was done to prevent the order of the tests affecting the performance of the children. For all three groups, the instructions were given verbally, in the language spoken by them.

3.5.2.1 Procedure for evaluating loudness perception in typically developing children. *Loudness growth identification* was measured with the typically developing children seated in a sound field set-up, 1 meter away from a loudspeaker placed at 0° azimuth. Initially, the sound-field thresholds and uncomfortable loudness level were established for each participant, separately for each of the six stimuli used in the study that included three warble-tones (500 Hz, 1000 Hz, & 4000 Hz) and three vowels (/u/, /a/, & /i/). This was done to determine the intensity range in which the loudness growth should be evaluated for each stimulus. Further, loudness growth identification was obtained for each stimulus using two methods, one where the intensity levels were changed sequentially (sequential method) and the other where it changed randomly (random method). The order in which these two methods were used was counterbalanced across the children.

In the sequential method, each stimulus was presented 5 dB above the threshold for a particular stimulus and progressed in 5 dB steps till it was 5 dB below the uncomfortable loudness level. The order in which the warble-tones or vowels was presented was randomised across the children. This randomization was done within each stimulus type (warble-tones & vowels). Further, the order in which the two types of stimuli were presented was also counterbalanced. These randomizations were done to prevent a stimulus order effect. For each stimulus, the loudness growth test was repeated thrice.

The random method was similar to the ISO 16832 procedure (Kinkel, 2007) and the procedure used by Al-Salim et al. (2010). As recommended in their techniques, the stimuli were presented in a pseudo-random sequence such that the entire dynamic range was covered (5 dB above the threshold & 5 dB below the uncomfortable level). The pseudo-random sequence of the intensity levels was created by dividing the entire dynamic range into five approximately equally spaced levels. The participants were first tested with a stimulus close to the midpoint so that they heard the initial stimulus at approximately the same loudness level. The remaining spaced levels were randomly selected. Additionally, the stimuli were also randomised within each of the five levels, as well as randomized within a stimulus type and between the stimulus type. It was ensured that every stimulus was heard thrice at each level, with the stimulus and presentation level being randomized.

The responses from the participants were obtained using the loudness growth chart, developed as a part of the study, placed in front of them on a table. The participants were instructed to point to the loudness level that best categorizes the sound heard by them. They were told that they may hear the same loudness level more than once. The loudness growth chart was changed each time a child showed signs of restlessness. If a child continued to show signs of inattention after changing the chart, he/she was given a break after which the testing was resumed.

The responses of the participants for the loudness growth identification test were tabulated on a response sheet (Appendix 2). This was done separately for the six stimuli as well as for the two methods of presentation (sequential & random).

Scoring of loudness growth: The responses were scored only if they were found to be consistent. Two different criteria were used to calculate the consistency of the responses of the loudness growth identification test. In the first criteria, the participant was required to have judged a particular presentation level to have the same loudness level at least twice out of the three presentations. Only responses that met the first criteria were further subjected to the second criteria. In the second criteria, the consistency of the growth in loudness perception was noted from the median loudness level of the three presentations. To calculate the median loudness value, the six loudness levels were coded (‘very soft’ = 1, ‘soft’ = 2, ‘comfortable’ = 3, ‘loud’ = 4, ‘too loud’ = 5, & ‘very loud & paining’ = 6). The median value was considered to be consistent if an increase in intensity level resulted in a signal being perceived as having either the same loudness level or an increase in loudness. Likewise, a decrease in intensity of a stimulus should have been perceived as having either the same loudness or decrease in loudness. Responses of children that did not meet the above two criteria were not included for the statistical analysis. Further, the average of the intensity range that led to the perception of a particular loudness level was calculated. The average intensity was calculated for the consistent responses for each loudness level for all six stimuli.

Intensity discrimination was measured using similar stimuli as that used to evaluate loudness growth (500 Hz, 1000 Hz, 4000 Hz warble-tones & the vowels /u/, /a/, /i/). The setup used to present the stimuli was also similar to that used to measure loudness growth. However, instead of an audiometer, the stimuli were presented from a laptop loaded with Psycon v2.18 software using scripts 1, 2, 3, and 4. The output from the laptop was sent to a loudspeaker. The thresholds were obtained using an adaptive tracking procedure (Figure 3.3). The intensity of the anchor signal was held constant as 50 dB HL using Script 1 for warble-tones and Script 3 for vowels. The variable interval (odd-ball interval) contained the louder stimulus, which was presented using Script 2 for warble-tones and Script 4 for vowels. Initially, the variable stimulus was set to be 10 dB louder than the anchor stimulus by keying in the value in the 'Initial value' tab in the software. Subsequent to this, the intensity of the variable interval was set to change in 5 dB steps for the next two reversals and in 2 dB steps for the following 4 reversals. A 2 down / 1 up rule was utilised, similar to that used by Whitmer and Akeroyd (2011).

Half of the participants heard the warble-tones first and the other half heard the vowels first. The responses were obtained using the three-alternative forced choice method, where the anchor was presented twice having the same intensity and the variable signal was presented once. The participants were instructed to select the interval having the different stimulus by lifting one, two or three fingers, indicating the first, second or the third interval, respectively. The responses given by the participants were marked by the examiner in the computer software. The average of the final four reversals served as the intensity discrimination threshold.

If required, the participants were given breaks if they showed any sign of being restless or tired. The entire evaluation of both loudness perception tests was completed in one session. The session lasted for around 2 to 2.5 hours, depending on the speed with which the children responded.

3.5.2.2 Procedure for evaluating loudness perception in children using cochlear implants. The procedure used to evaluate the two loudness perception tests in children using cochlear implants was similar to that done for the typically developing children. Those participants who wore hearing aids in their non-implanted ear were made to remove them during the evaluation. The children were tested using the program and the map setting recommended to be used regularly by qualified audiologists. Details of the device and the settings used in the cochlear implant processor are provided in Table 3.1.

In addition to what was done for the typically developing children, extra measures were taken to ensure that the children using cochlear implants understood the instructions to carry out the test. This was done by demonstrating the tasks for each of the loudness perception measures. The investigator first demonstrated the tasks by doing them herself with the help of a caregiver. Following this, each child was given practice using a few stimuli for each of the tests. Children who did not follow the activities were again instructed and were asked to do the practice items again. The stimulus used for the practice (250 Hz warble-tone) was not utilised during the actual evaluation. The time taken to test the children using cochlear implants was approximately 2 to 2.5 hours.

As done with the typically developing children, the responses of the children using cochlear implants were tabulated and scored later. This was done for both the loudness perception tests that were evaluated.

3.5.2.3 Procedure for evaluating loudness perception in the children using hearing aids. The children using hearing aids were tested with their own hearing aids in the prescribed settings that enabled them to obtain warble-tone thresholds well within the speech spectrum from 250 Hz to 4 kHz. Additionally, they were evaluated with a pair of ‘test hearing aids’ (Audio service, Model HP 4 G3). The two test-digital-BTE hearing aids chosen for the study had a fitting range suitable for those with moderate to severe hearing loss, four channels, provision to load at least three programs, and options to vary the compression parameters.

Prior to evaluating the loudness growth of each child, the ‘test hearing aids’ were programmed separately for each ear using the Audioservice software, Connexx 8. The first-fit, obtained using the DSLv5 fitting formula (Cornelisse et al., 1995), was loaded as the first program in the hearing aids. This fitting formula was selected as it has been reported by Scollie et al. (2010) to be a reliable threshold based formula for providing gain for children. In addition, each hearing aid was loaded with two more programmes. For half of the participants, the second programme had a linear setting and the third had a non-linear setting. For the other half of the participants, the non-linear setting was loaded in the second program and linear setting was loaded in the third program. The compression parameters chosen were those known to not affect speech intelligibility (Dillon, 2001). For the linear setting, the compression ratio was set to 1:1 and the tab for compression kneepoint was switched ‘off’. However, for the non-linear setting, the compression ratio was set to 3.1:1 and the compression kneepoint was set at 50 dB SPL. Other default parameters in the software were retained in the hearing aid.

If the settings of the ‘test hearing aids’ resulted in the aided warble-tone thresholds falling at the bottom or out of the speech spectrum, fine tuning was done by increasing the gain in different channels. The gain was increased gradually till the child confirmed that she/he could hear sounds across the frequencies from 250 Hz to 4 kHz.

Confirmation that the compression parameters in the ‘test hearing aids’ were as required, was obtained using a Fonix 8000 hearing aid test system. This was done for each participant’s hearing aid by checking the compression parameters along with the input/output curve values at 2000 Hz. The frequency 2000 Hz was selected as per the recommendations of ANSI S3.22-1996. If the compression kneepoint was not as required, it was manipulated using the Audioservice software that was used to program the hearing aids, until the required values were obtained.

The loudness growth identification and intensity discrimination tests were conducted thrice for the children using hearing aids, as mentioned earlier. The tests were conducted in a similar manner as was done for the typically developing children. However, for the loudness growth identification test, only the random order method of stimulus presentation was chosen. These children were evaluated only with the random order method as Tak and Yathiraj (2019b) noted that typically developing children and children using cochlear implants responded in a similar manner using either the random or sequential order methods. As it has been reported in literature that more consistent responses were obtained using a random order method (Baird et al., 1991), it was utilised to test the children using hearing aids.

The testing was first done with the participants wearing their own binaural hearing aids in the prescribed settings. The purpose of evaluating them with their prescribed hearing aids was to determine if the findings with the 'test-hearing aids' could be generalised to hearings aids used in day-to-day situations. The prescribed hearing aids had non-linear programs loaded with the compression ranging from 1.1:1 to 4:1.

Subsequent to evaluating the children with their own hearing aids, all the participants were evaluated with the 'test hearing aids', set with two different programs. Half the participants were tested with the linear program first and another half with the non-linear program first. As the children were evaluated multiple times, the testing was conducted over three sessions, with each session lasting approximately 1.5 to 2 hours. Children who showed signs of restlessness or inattentiveness during a session were provided breaks.

3.6 Test-retest Reliability

Test-retest reliability for intensity discrimination was done on ~10% of the participants from each group. It was done for 3 out of the 31 typically developing children (9.68%), 3 out of the 25 children using cochlear implants (12%), and 2 out of 20 children using hearing aids (10%). The re-test was done within a period of two months after the first evaluation. The test-rest reliability was not done for the loudness growth test as the children were tested thrice with each stimulus.

3.7 Statistical Analyses

The analysis of loudness growth identification test responses was done only for those participants who gave valid responses, based on the criteria given earlier. However, for the intensity discrimination test, thresholds of all participant were evaluated.

The data were statistical analysed using the Statistical Package for Social Science (Version 21). Shapiro-Wilk test of normality was done for the responses obtained for each of the six different stimuli used for the two loudness perception tests. This was done for each participant group separately. The results indicated that many variables were not normally distributed (Appendices 3 to 6). Thus, non-parametric statistics were utilised.

Both descriptive and inferential statistics were done to compare the loudness growth identification and intensity discrimination in each of the three participant groups. Within group comparison was done using Friedman test followed by Wilcoxon signed rank test when required. Between group comparison was done using Kruskal Wallis test along with Mann-Whitney U tests of statistics, if required. The results were also cross-validated using Bayesian statistics.

4. Results

The results are provided for the typically children developing children and the two groups of children using listening devices. The data were analysed only for those who gave consistent responses. The test stimuli used in different listening conditions served as the independent variables and the responses to the two loudness perception tests formed the dependent variables. The data of the three groups were analysed separately for each of the six stimuli.

Prior to the analyses, Shapiro-Wilk test of normality was calculated for each participant group, stimulus, and loudness levels. The findings indicated that a few variables were not normally distributed in all three participant groups (Appendices 3 to 6). Hence, as per the recommendations of Nahm (2016), non-parametric statistical tests were conducted.

The results are given under the following subheadings:

- 4.1 Effect of stimulus-order presentation (random & sequential) on intensity required to identify loudness levels
  - 4.1.1 In typically developing children,
  - 4.1.2 In children using cochlear implants.
- 4.2 Comparison of loudness perception across three different device-conditions in children using hearing aids
  - 4.2.1 Comparison of intensity required to identify loudness levels across three different device-conditions (own prescribed hearing aids, ‘test hearing aids’ in linear setting, & ‘test hearing aids’ in non-linear setting),

    - 4.2.2 Comparison of intensity discrimination across three different device-conditions (own prescribed hearing aids, ‘test hearing aids’ in linear setting, & ‘test hearing aids’ in non-linear setting).
- 4.3 Comparison of intensity required to identify loudness levels between
    - 4.3.1 Typically developing children, children using cochlear implants and children using their own prescribed hearing aids,
    - 4.3.2 Typically developing children, children using cochlear implants and children using the ‘test hearing aids’ in linear setting,
    - 4.3.3 Typically developing children, children using cochlear implants and children using the ‘test hearing aids’ in non-linear setting.
- 4.4 Comparison of intensity discrimination between
    - 4.4.1 Typically developing children, children using cochlear implants, and children using own prescribed hearing aids,
    - 4.4.2 Comparison across typically developing children, children using cochlear implants, and children using ‘test hearing aids’ in linear setting,
    - 4.4.3 Comparison across typically developing children, children using cochlear implants, and children using ‘test hearing aids’ in non-linear setting.

4.1 Effect of Stimulus-Order Presentation (Random & Sequential) on Intensity Required to Identify Loudness Levels

The effect of random and sequential order of stimulus presentation on intensity required to identify each of the five loudness levels was obtained from the typically developing children and the children using cochlear implants. This analysis was done on typically developing children and one of the clinical groups in order to choose one stimulus-order presentation for the rest of the analysis. Within the two groups in whom the analysis was conducted, the number of participants who could identify a particular loudness level as a function of the stimulus intensity varied (Figure 4.1 & Figure 4.2). This variation occurred as not all participants perceived each of the six loudness levels. Thus, the data were analysed for all 31 typically developing children, who gave consistent responses, but were analysed only for 12 of the 25 children using cochlear implants who gave valid responses.

4.1.1 Effect of Random and Sequential Order Methods on Intensity Required to Identify Loudness Levels in Typically Developing Children

Marginal variations were observed between the random order and sequential order methods, based on the mean, standard deviation, median, as well as the 25th and 75th percentile of the intensity required to perceive each loudness level (Table 4.1, Table 4.2 & Figure 4.1). This was observed for most of the stimuli. For several of the stimuli, at the lower loudness levels the participants needed lower intensities to perceive the loudness in the random order method compared to the sequential order method. On the other hand, at higher presentation levels the participants required higher intensities to perceive the loudness level using the random order method than the sequential order method. To confirm if these differences were statistically different, Wilcoxon signed-rank test was performed for each stimulus and each loudness level separately.

Table 4.1

Mean and median intensity levels (in dB HL) with standard deviation (SD), 25th - 75th percentile (Q1 - Q3) in parenthesis, and significance of difference for warble-tones presented randomly and sequentially in the typically developing children

Stimuli	**Loud-ness level**	**Random method**			**Sequential method**						
		n	**Mean (SD)**	**Median (Q1 – Q3)**	***n***	**Mean (SD)**	**Median (Q1 – Q3)**	***z***	***p***	***r***	***BF*₁₀**
500 Hz	VS	31	22.74 (4.67)	25 (20 - 25)	30	24.42 (5.03)	25 (20 - 27.5)	-2.15	0.03*	-0.39	1.70
	S	31	43.87 (6.01)	45 (40 - 47.5)	30	46.67 (5.51)	47.5 (41.87 - 52.5)	-2.33	0.02*	-0.43	2.76
	C	31	64.03 (4.12)	65 (62.5 - 67.5)	30	64.25 (4.11)	65 (61.87 - 67.5)	-0.25	0.81	-0.05	0.21
	L	30	82.08 (6.43)	80 (77.5 - 87.5)	30	79.50 (4.97)	80 (76.87 - 82.5)	-1.84	0.07	-0.34	1.16
	TL	23	93.80 (2.81)	92.5 (92.5 - 95)	26	94.04 (2.24)	95 (92.5 - 95)	-0.57	0.57	-0.12	0.25
1000 Hz	VS	30	22.08 (4.74)	22.5 (17.5 - 25.63)	30	24 (6.07)	23.75 (20 - 27.5)	-2.59	0.01*	-0.48	6.14
	S	30	46.83 (6.88)	47.5 (41.87 - 52.5)	30	48.17 (8.58)	51.25 (40 - 55)	-0.68	0.50	-0.13	0.25
	C	31	68.71 (5.66)	67.5 (65 - 70)	30	66.42 (6.81)	67.5 (60 - 70.62)	-1.32	0.19	-0.24	0.51
	L	31	88.14 (5.98)	90 (82.5 - 92.5)	30	82.67 (7.10)	83.75 (78.75 - 87.5)	-3.31	0.001**	-0.60	70.50
	TL	16	100.16 (3.09)	100 (97.5 - 102.5)	29	98.36 (3.55)	97.5 (95 - 100)	-2.56	0.01*	-0.64	14.64
4000 Hz	VS	31	24.84 (6.16)	25 (22.5 - 27.5)	30	27.33 (5.29)	27.5 (25 - 30)	-2.57	0.01*	-0.47	4.03
	S	31	51.53 (7.60)	52.5 (47.5 - 55)	30	53.83 (8.43)	55 (50 - 60)	-1.67	0.10	-0.30	0.83
	C	31	73.63 (4.65)	75 (70 - 75)	30	72.75 (8.05)	73.75 (67.5 - 78.12)	-0.61	0.55	-0.11	0.25
	L	31	90.73 (5.96)	90 (87.5 - 95)	30	88.08 (8.19)	87.5 (81.87 - 95)	-1.69	0.09	-0.31	1.00
	TL	27	104.44 (3.28)	105 (102.5 - 107.5)	27	102.59 (3.70)	102.5 (100 - 105)	-2.28	0.02*	-0.46	3.40

Note. VS = Very Soft; S = Soft; C = Comfortable; L = Loud; TL = Too loud; * = $p < 0.05$; ** = $p < 0.01$; *r* (effect size) = $z/\sqrt{n}$; BF_{10} = Bayes factor favouring the alternate hypothesis.

Table 4.2

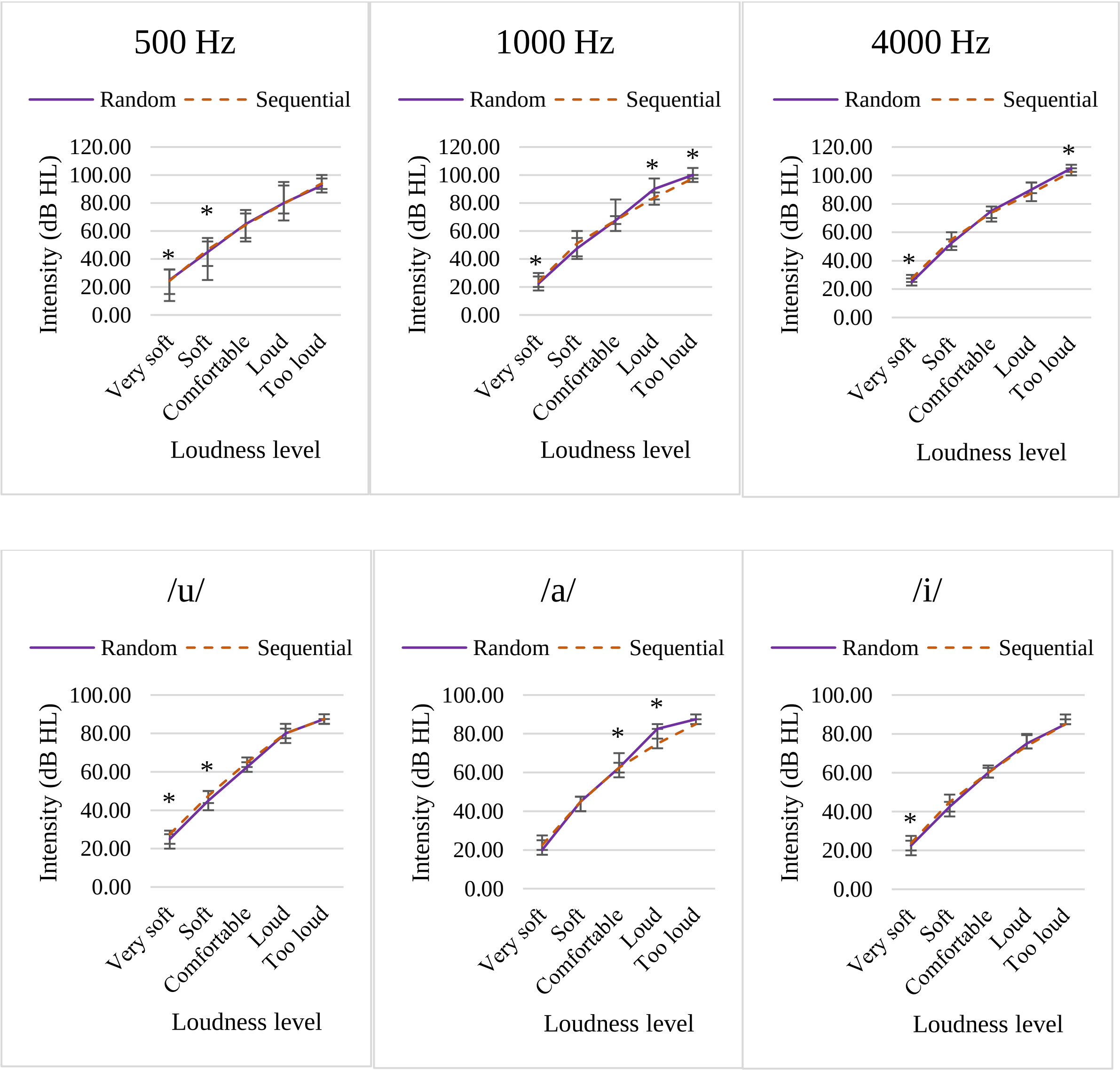
Mean and median intensity levels (in dB HL) with standard deviation (SD) and 25th - 75th percentile (Q1 - Q3) in parenthesis, and significance of difference for vowels presented randomly and sequentially in the typically developing children

Stimuli	**Loudness level**	**Random method**			**Sequential method**			***Z***	***p***	***r***	***BF10***
		n	**Mean (SD)**	**Median (Q1 – Q3)**	***n***	**Mean (SD)**	**Median (Q1 - Q3)**				
/u/	VS	30	24.17 (4.79)	25 (20 - 27.5)	28	26.16 (6.14)	27.5 (22.5 - 29.38)	-2.42	0.02*	-0.46	4.64
	S	31	44.11 (5.79)	45 (40 - 47.5)	29	46.98 (6.35)	47.5 (43.75 - 50)	-2.42	0.02*	-0.45	4.23
	C	31	63.55 (5.07)	62.5 (60 - 67.5)	29	65.09 (4.89)	65 (62.5 - 67.5)	-1.96	0.05	-0.36	1.02
	L	29	80.34 (4.18)	80 (77.5 - 82.5)	27	79.26 (5.36)	80 (75 - 85)	-1.08	0.28	-0.21	0.39
	TL	11	87.50 (2.24)	87.5 (85 - 90)	14	87.14 (2.16)	87.5 (85 - 90)	-1.51	0.13	-0.53	0.69
/a/	VS	31	21.85 (5.24)	20 (20 - 25)	29	22.59 (5.24)	22.5 (17.5 - 27.5)	-1.03	0.30	-0.19	0.33
	S	31	44.43 (6.31)	45 (40 - 47.5)	29	43.79 (6.50)	45 (40 - 47.5)	-0.56	0.57	-0.10	0.22
	C	31	64.68 (5.47)	62.5 (60 - 70)	29	61.21 (4.80)	62.5 (57.5 - 65)	-3.01	0.003**	-0.56	28.40
	L	23	80.76 (4.49)	82.5 (77.5 - 85)	28	76.61 (5.32)	75 (72.5 - 82.5)	-3.12	0.002**	-0.68	21.28
	TL	10	87.50 (2.63)	87.5 (85 - 90)	16	86.25 (1.58)	85 (85 - 87.5)	-1.24	0.21	-0.44	0.46
/i/	VS	30	21.41 (5.03)	22.5 (17.5 - 25)	28	23.57 (5.20)	23.75 (20 - 27.5)	-2.42	0.02*	-0.47	4.40
	S	31	41.45 (6.79)	42.5 (37.5 - 45)	29	44.39 (6.83)	45 (40 - 48.75)	-1.99	0.05	-0.37	1.47
	C	31	60.89 (5.90)	60 (57.5 - 62.5)	29	61.03 (5.11)	60 (57.5 - 63.75)	-0.32	0.76	-0.06	0.21
	L	29	76.64 (5.23)	75 (72.5 - 80)	28	75.27 (5.06)	73.75 (72.5 - 79.38)	-0.98	0.33	-0.19	0.32
	TL	18	86.39 (2.87)	85 (85 - 90)	20	86.37 (2.06)	85 (85 - 87.5)	-0.49	0.62	-0.13	0.28

Note. VS = Very Soft; S = Soft; C = Comfortable; L = Loud; TL = Too loud; * = $p < 0.05$; ** = $p < 0.01$; r (effect size) = $z/\sqrt{n}$; BF_{10} = Bayes factor favouring the alternate hypothesis.

Figure 4.1

Median, 25th - 75th percentile and significance of difference of intensities at different loudness levels using random and sequential order of stimulus presentation in typically developing children



Note. * = p < 0.05, measured using Wilcoxon signed-rank test

The Wilcoxon signed-rank test (Table 4.1 & Table 4.2) indicated that there were significant differences at most of the extreme loudness levels. The random method required significantly lower intensity than the sequential method for the ‘very soft’ rating, but significantly higher intensity for the ‘loud’ or ‘too loud’ levels. However, this difference varied depending on the stimuli used.

4.1.2 Effect of Random and Sequential Order Methods on Intensity Level to Identify Specific Loudness Level in Children Using Cochlear Implants

From the mean and median values of the intensity needed to perceive different loudness levels given in Table 4.3 and Table 4.4, it can be seen that the children using cochlear implants preformed similarly in the random and sequential methods. This is also evident in Figure 4.2. To determine whether a significant difference occurred between the two stimulus presentation methods, Wilcoxon signed-rank test was performed. No significant difference was noted between the two presentation methods for any of the loudness levels for all six stimuli. An exception to this was seen for the 1000 Hz stimulus (Table 4.3), where a significant difference was noted for ‘comfortable’, ‘loud’ and ‘too loud’ levels of the stimuli.

Thus, the evaluations done in the typically developing children and children using cochlear implants indicated that they performed differently on the two methods of stimulus presentation. While the typically developing children obtained significantly lower intensity for the random method, primarily in the extreme lower loudness levels and higher intensity in high loudness levels. This was observed for most of the stimuli. On the other hand, the children using cochlear implants overall obtained comparable responses in the two methods. The high Bayes factor values (Tables 4.1, 4.2 & 4.3) for the intensity levels that were significantly different, using the two stimulus-order methods (random & sequential), substantiated the findings that were obtained.

Table 4.3

Mean and median intensity levels (dB HL) with standard deviation (SD) and 25th - 75th percentile (Q1 – Q3) in parenthesis, and significance of difference for warble-tones using random order and sequential order methods in children using cochlear implants

Stimuli	**Loudness level**	**Random method**			**Sequential method**			***z***	***p***	***r***	***BF_{10}***
		n	**Mean (SD)**	**Median (Q1 – Q3)**	***n***	**Mean (SD)**	**Median (Q1 – Q3)**				
500 Hz	VS	10	34.25 (6.88)	35 (28.75 - 40.63)	9	34.44 (4.47)	37.5 (32.5 - 42.5)	-0.5	0.61	-0.17	0.35
	S	12	47.08 (7.52)	48.75 (41.25 - 52.5)	11	47.04 (5.10)	50 (45 - 57.5)	-1.34	0.18	-0.40	0.69
	C	12	69.37 (7.69)	68.75 (63.13 - 77.5)	11	66.82 (8.07)	70 (62.5 - 77.5)	-0.42	0.68	-0.13	0.31
	L	8	85.31 (7.13)	85 (80 - 88.75)	9	81.11 (8.49)	81.25 (77.5 - 86.25)	-0.93	0.35	-0.35	0.54
	TL	6	95 (2.74)	95 (92.5 - 96.25)	8	96.56 (4.62)	95 (92.5 - 95)	0	1	0.00	0.47
1000 Hz	VS	11	37.5 (6.22)	33.75 (29.38 - 37.5)	10	33 (4.83)	35 (31.25 - 37.5)	-0.95	0.34	-0.32	0.48
	S	11	51.82 (8.22)	45 (42.5 - 51.88)	12	46.88 (5.75)	47.5 (45 - 50)	-0.31	0.76	-0.09	0.30
	C	11	70 (8.94)	68.75 (65 - 75)	12	69.58 (6.98)	65 (60 - 72.5)	-2.06	0.04*	-0.62	2.46
	L	8	81.56 (5.16)	88.75 (81.88 - 95.63)	10	89.25 (7.06)	80 (75 - 87.5)	-2.68	0.007**	-0.89	33.77
	TL	6	94.17 (1.29)	100 (100 - 102.5)	6	100.83 (1.29)	96.25 (93.13 - 99.38)	-2.04	0.04*	-0.91	5.71
4000 Hz	VS	10	33.75 (3.39)	35 (30 - 37.5)	8	36.25 (4.43)	36.25 (33.13 - 37.5)	-1.19	0.24	-0.42	0.62
	S	12	45.63 (6.58)	45 (42.5 - 47.5)	11	47.05 (6.97)	50 (45 - 50)	-0.88	0.38	-0.27	0.43
	C	12	72.08 (8.97)	68.75 (65.63 - 81.88)	11	71.59 (9.44)	67.5 (65 - 82.5)	-0.24	0.81	-0.07	0.33
	L	8	87.5 (7.90)	85 (81.25 - 95.63)	8	87.5 (10.69)	83.75 (80 - 96.88)	-0.92	0.36	-0.35	0.51
	TL	8	104.37 (4.17)	102.5 (100.63 - 109.38)	6	101.67 (2.04)	101.25 (100 - 103.13)	-1.63	0.10	-0.67	1.42

Note. VS = Very Soft; S = Soft; C = Comfortable; L = Loud; TL = Too loud; * = $p < 0.05$; ** = $p < 0.01$; *r* (effect size) = $z/\sqrt{n}$; BF_{10} = Bayes factor favouring the alternate hypothesis

Table 4.4

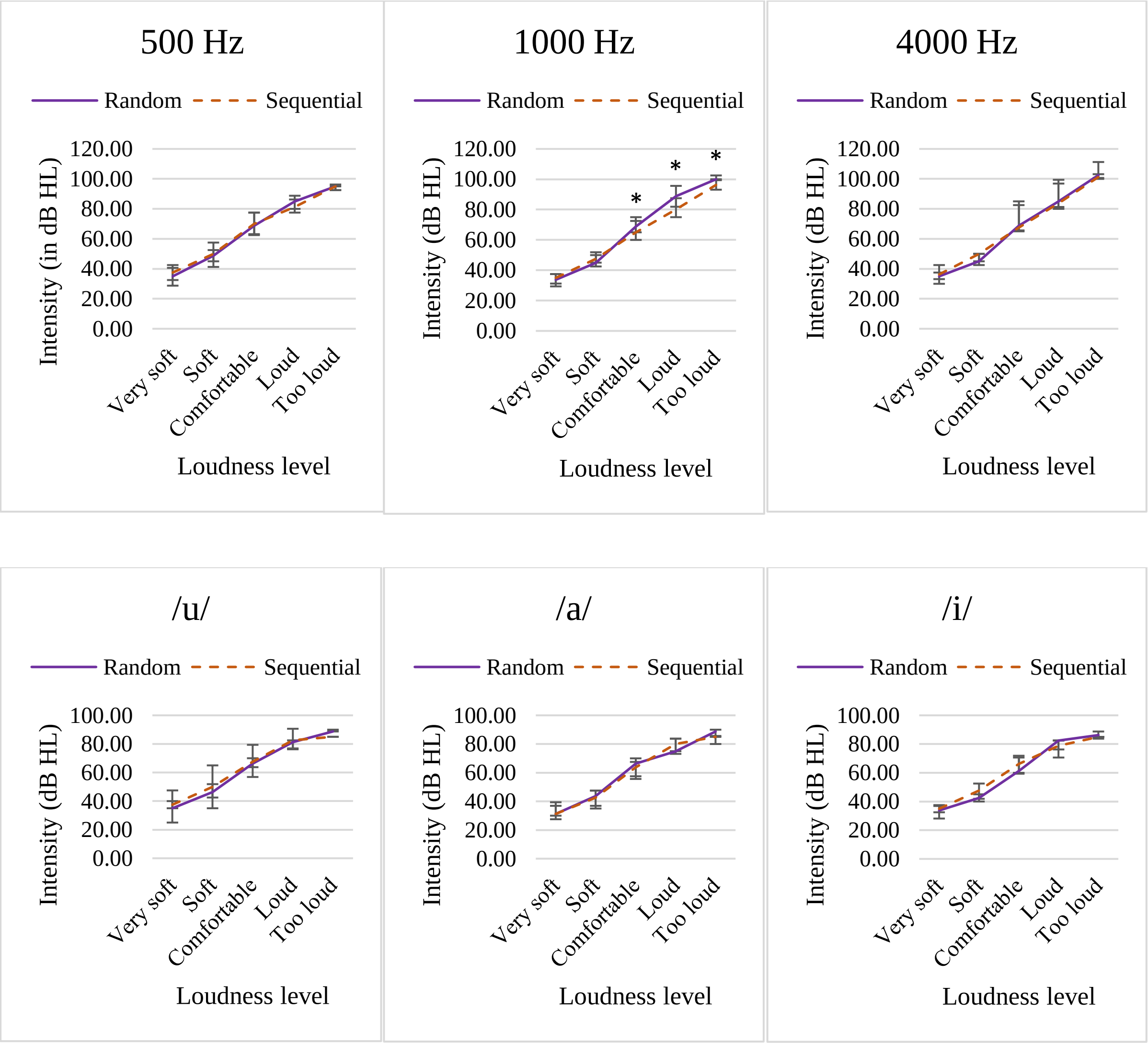
Mean and median intensity levels (dB HL) with standard deviation (SD) and 25th - 75th percentile (Q1 - Q3) in parenthesis, and significance of difference for vowels using random order and sequential order methods in children using cochlear implants

Stimuli	**Loudness level**	**Random method**			**Sequential method**						
		n	**Mean (SD)**	**Median (Q1 – Q3)**	***n***	**Mean (SD)**	**Median (Q1 – Q3)**	***z***	***p***	***r***	BF_{10}
/u/	VS	8	35.31 (6.04)	35 (30 - 40)	7	38.93 (5.56)	37.5 (35 - 45)	-1.63	0.10	-0.62	1.12
	S	12	46.67 (6.60)	46.25 (40.63 - 51.83)	11	49.32 (8.22)	50 (42.5 - 57.5)	-1.27	0.20	-0.38	0.71
	C	12	67.5 (6.99)	66.25 (62.5 - 71.88)	10	68.25 (7.27)	67.5 (63.75 - 75.63)	-0.09	0.93	-0.03	0.31
	L	8	81.25 (3.27)	81.25 (80 - 84.38)	8	80.62 (5.63)	82.5 (76.25 - 84.38)	-0.18	0.85	-0.07	0.36
	TL	2	88.75 (1.77)	88.75 (88.75 – 88.75)	2	85 (0)	85 (85 - 85)	$^{\#}$--	$^{\#}$--	$^{\#}$--	$^{\#}$--
/a/	VS	8	33.12 (4.96)	31.25 (30 - 36.88)	8	32.81 (6.47)	31.25 (27.5 - 39.38)	-1	0.32	-0.38	0.52
	S	12	42.92 (6.73)	43.75 (36.88 - 47.5)	11	43.18 (7.75)	42.5 (35 - 47.5)	-0.43	0.67	-0.13	0.32
	C	12	63.12 (6.41)	66.25 (55.63 - 67.5)	10	63.25 (7.36)	63.75 (57.5 - 70)	-0.24	0.81	-0.08	0.31
	L	9	79.17 (5.99)	75 (75 - 83.75)	8	77.5 (7.44)	80 (73.13 - 83.75)	-0.85	0.40	-0.30	0.53
	TL	4	88.12 (2.39)	88.75 (85.63 - 90)	3	84.17 (3.82)	85 (80 - 85)	-1	0.32	-0.71	0.73
/i/	VS	8	33.75 (5.82)	33.75 (28.13 - 36.88)	9	35 (4.33)	35 (32.5 - 37.5)	-1.3	0.19	-0.46	0.65
	S	12	44.17 (5.97)	42.5 (40 - 45)	10	46.75 (6.24)	47.5 (41.88 - 52.5)	-0.82	0.41	-0.26	0.41
	C	12	64.37 (6.75)	61.25 (60 - 71.88)	10	64.75 (7.12)	66.25 (59.38 - 70.63)	-0.57	0.57	-0.18	0.32
	L	9	80.28 (4.91)	82.5 (76.25 - 82.5)	8	76.56 (6.67)	78.75 (70.63 - 82.5)	-1.16	0.25	-0.41	0.72
	TL	2	86.25 (1.77)	86.25 (85 – 86.25)	5	86 (2.85)	85 (83.75 – 88.75)	0	1	0.00	0.53

Note. VS = Very Soft; S = Soft; C = Comfortable; L = Loud; TL = Too loud; *r* (effect size) = $z/\sqrt{n}$; BF_{10} = Bayes factor favouring the alternate hypothesis; $^{\#}$ = not measured as very few participants chose the loudness level.

Figure 4.2

Median, 25th - 75th percentile (Q1 – Q3) and significance of difference of intensity at different loudness levels using random and sequential order of stimulus presentation in children using cochlear implants



Note. * = $p < 0.05$, measured using Wilcoxon signed-rank test.

From the findings comparing the random and sequential order of stimulus presentation, it could be seen that for most loudness levels measured for each stimulus, the two methods did not differ. This was especially more prominent in the children using cochlear implants. Hence, further measurement / analyses were done using the random order method, which is also reported in literature to result in less bias (Baird et al., 1991; Beattie et al., 1997)

4.2 Comparison of Loudness Perception across Three Different Device Conditions in Children Using Hearing Aids

Comparison of the intensity required to identify different loudness levels in children using hearing aids, using the random order method, was done for the for three hearing aid conditions. The conditions varied depending on the hearing aids worn by the children which included their own hearing aids, 'test hearing aids' with linear setting, and 'test hearing aids' with non-linear setting. The data were analysed only for the 13 out of the 20 children who gave valid responses.

4.2.1 Comparison of Intensity Required to Identify Loudness Levels with Own Prescribed Hearing Aids, 'Test Hearing Aids' in Linear Setting and 'Test Hearing Aids' in Non-Linear Settings

The mean and median intensity required to perceive each loudness level for the three hearing aid conditions are depicted in Table 4.5 and Table 4.6 for the warble-tones and vowels, respectively. From the tables it can be seen that there were marginal differences among the three hearing aid conditions. For most stimuli, the participants perceived the signals as being 'very soft' at a lower intensity with 'test hearing aid' in the non-linear setting compared to the linear setting as well as their own hearing aids. At the higher loudness levels, the intensity required was similar for all the hearing aid conditions. This was observed for all stimuli, except for the 1 kHz warble-tone. Also, only a few participants perceived the signals as being 'too loud'.

Table 4.5

Mean and median intensity (dB HL) with standard deviation (SD) and 25th -75th percentile (Q1 – Q3) in parenthesis for warble-tones for the three conditions in children using hearing aids.

Stimuli		**Hearing Aid Conditions**								
		Own			**Linear**			**Non-linear**		
		n	**Mean (SD)**	**Median (Q1 – Q3)**	***n***	**Mean (SD)**	**Median (Q1 – Q3)**	***n***	**Mean (SD)**	**Median (Q1 – Q3)**
500 Hz	VS	9	38.33 (7.40)	35 (31.25 - 45)	10	39 (8.10)	41.25 (31.88 - 45.625)	8	33.44 (9.72)	32.5 (26.25 - 43.75)
	S	13	51.15 (6.66)	52.5 (46.25 - 57.5)	13	50.96 (8.07)	52.5 (48.75 - 56.25)	12	48.96 (11.99)	52.5 (40 - 55)
	C	12	67.29 (3.91)	67.5 (63.75 - 70)	13	70.38 (8.65)	67.5 (65 - 76.25)	12	72.71 (10.52)	70 (67.5 - 74.38)
	L	13	85.58 (5.02)	85 (81.25 - 90)	10	88.25 (4.42)	88.75 (84.38 - 92.5)	9	91.39 (4.35)	92.5 (87.5 - 95)
	TL	8	97.5 (2.31)	97.5 (95 - 100)	4	98.12 (1.25)	97.5 (97.5 - 99.38)	1	95 †	95 †
1 kHz	VS	9	35.83 (6.85)	37.5 (30 - 41.25)	10	39.75 (6.82)	40 (33.75- 43.125)	8	40.62 (8.10)	41.25 (31.88 - 48.75)
	S	13	50.19 (5.15)	50 (46.25 - 55)	12	51.25 (5.79)	52.5 (47.5- 55)	12	57.08 (8.78)	55 (48.13 - 66.25)
	C	13	67.69 (4.62)	67.5 (63.75 - 70)	13	67.88 (10.55)	65 (60 - 77.5)	12	79.37 (12.39)	75 (72.5 - 89.37)
	L	13	86.35 (5.65)	85 (83.75 - 88.75)	11	85.91 (8.46)	85 (77.5 - 92.5)	8	92.81 (5.89)	93.75 (88.12- 97.5)
	TL	7	101.07 (1.97)	102.5 (100 - 102.5)	6	98.75 (2.62)	98.75 (96.88 - 100.63)	1	102.5 †	102.5 †
4 kHz	VS	9	43.05 (10.06)	42.5 (38.75 - 51.25)	9	40.56 (9.90)	37.5 (31.25- 50)	7	45 (9.13)	42.5 (37.5 - 55)
	S	13	57.50 (9.35)	57.5 (53.75 - 63.75)	12	49.58 (6.38)	48.75 (45- 55)	11	55.68 (10.07)	55 (50 - 65)
	C	13	76.54 (9.82)	77.5 (68.75 - 85)	13	70.77 (10.92)	70 (63.75 - 80)	12	74.58 (14.41)	72.5 (65 - 89.38)
	L	11	95.45 (8.72)	97.5 (85 - 102.5)	11	93.18 (9.23)	95 (90 - 100)	9	94.72 (8.24)	97.5 (88.75 - 100)
	TL	5	103 (2.09)	102.5 (101.25 - 105)	4	106.25 (3.23)	106.25 (103.13 - 109.38)	2	105 (3.54)	105 (102.5 - 105)

Note. VS = Very soft; S = Soft; C = Comfortable; L = Loud; TL = Too loud; † = SD and Q1 – Q3 are not provided as there was only one participant.

Table 4.6

Mean and median intensity (dB HL) with standard deviation (SD) and 25th - 75th percentile (Q1 – Q3) in parenthesis for vowels for three conditions in children using hearing aids.

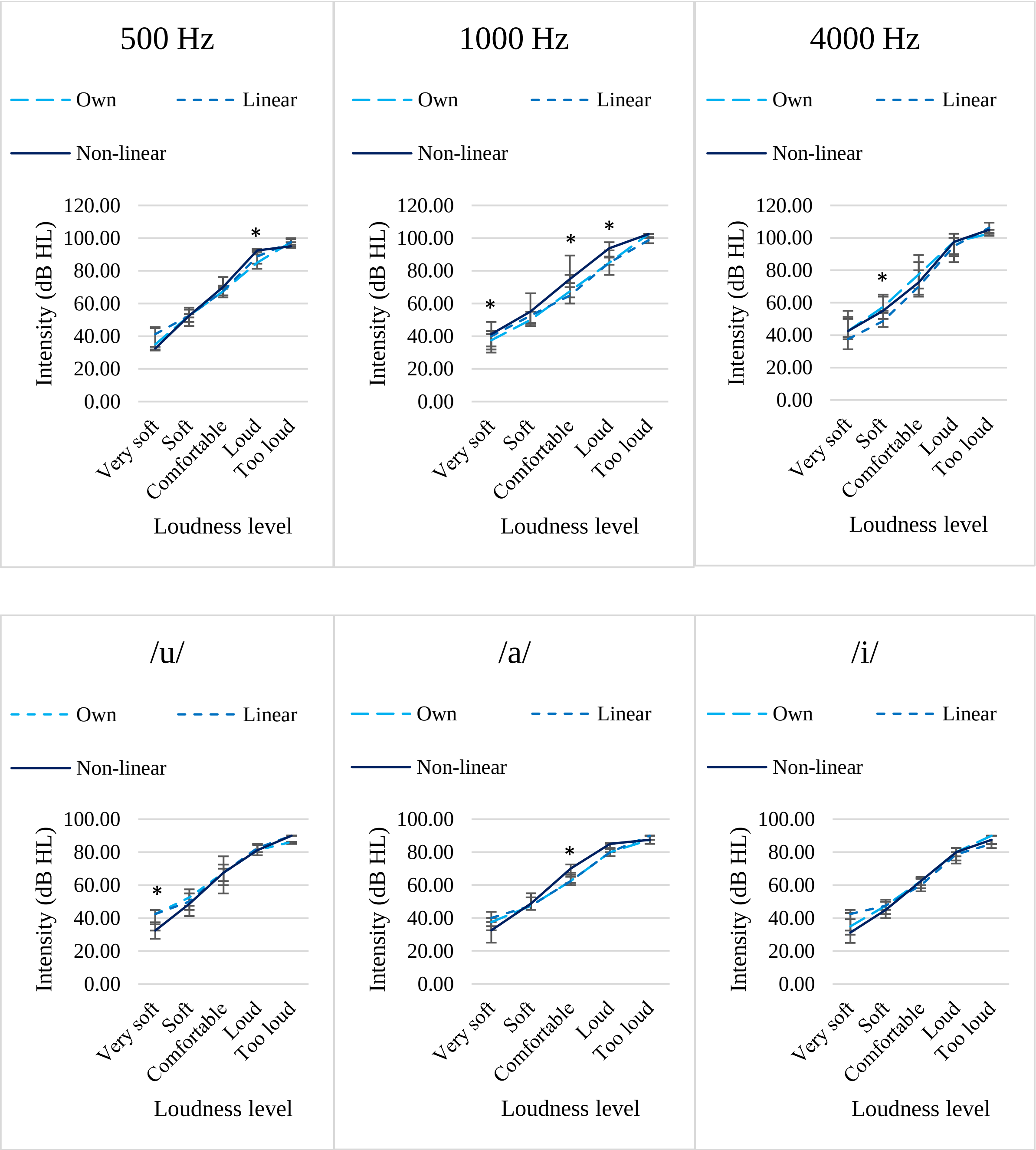
Stimuli		**Hearing Aid Conditions**								
		Own			**Linear**			**Non-linear**		
		n	**Mean (SD)**	**Median (Q1 – Q3)**	***n***	**Mean (SD)**	**Median (Q1 – Q3)**	***n***	**Mean (SD)**	**Median (Q1 – Q3)**
/u/	VS	9	40.28 (5.22)	42.5 (36.25 - 45)	9	40.28 (7.01)	42.5 (32.5 - 45)	7	33.21 (6.24)	32.5 (27.5- 37.5)
	S	13	49.81 (8)	52.5 (41.25 - 57.5)	13	50.77 (5.63)	50 (47.5 - 55)	12	48.96 (6.86)	48.75 (45- 55)
	C	13	65.58 (8.91)	67.5 (55 - 72.5)	13	66.73 (6.16)	67.5 (62.5 - 70)	11	68.64 (9.18)	67.5 (60 - 77.5)
	L	12	81.25 (5.06)	81.25 (78.13 - 85)	12	82.71 (4.58)	82.5 (80 - 85)	8	81.25 (3.27)	81.25 (80 - 84.38)
	TL	2	86.25 (1.77)	86.25 (85 - 86.25)	2	90 (0)	90 (90 - 90)	2	90 (0)	90 (90 - 90)
/a/	VS	11	36.59 (9.37)	37.5 (32.5 - 40)	9	38.89 (6.26)	40 (35 - 43.75)	7	32.14 (5.85)	32.5 (25 - 37.5)
	S	13	47.88 (7.83)	47.5 (45 - 52.5)	13	49.04 (6.58)	47.5 (45 - 55)	12	48.75 (5.17)	48.75 (45 - 52.5)
	C	13	63.46 (5.36)	62.5 (60 - 67.5)	13	63.46 (4.51)	62.5 (61.25 - 66.25)	11	69.54 (5.90)	70 (65 - 72.5)
	L	13	80 (5)	80 (77.5 - 85)	12	80.62 (2.17)	80 (80 - 82.5)	10	83 (5.11)	85 (81.88 - 85.63)
	TL	5	87.5 (2.50)	87.5 (85 - 90)	1	90 †	90 †	1	87.5 †	87.5 †
/i/	VS	10	36.25 (7.75)	35 (32.5 - 43.13)	7	38.21 (7.32)	42.5 (30 - 45)	8	31.25 (7.79)	31.25 (25 - 39.38)
	S	13	46.73 (6.24)	47.5 (45 - 51.25)	13	45.58 (5.60)	47.5 (42.5 - 50)	12	45.21 (7.11)	45 (40- 50)
	C	13	61.73 (4.61)	62.5 (60 - 63.75)	13	60.38 (6.68)	60 (56.25 - 65)	12	63.12 (7.70)	62.5 (58.13 - 64.38)
	L	13	80.77 (3.44)	80 (77.5 - 82.5)	12	77.92 (6.20)	78.75 (73.13 - 80)	11	79.77 (5.53)	80 (75 - 82.5)
	TL	3	90 (0)	90 (90 - 90)	3	85 (2.50)	85 (82.5 - 85)	3	86.67 (1.44)	87.5 (85 - 87.5)

Note. VS = Very soft; S = Soft; C = Comfortable; L = Loud; TL = Too loud; † = SD and Q1 – Q3 are not provided as there was only one participant.

To determine if the intensity required to perceive a particular loudness level varied significantly across the three hearing aid conditions, Friedman tests was done. This was calculated for each loudness level and each stimulus (Table 4.7). The significant difference observed between the hearing aid conditions varied depending on the loudness level and the stimulus.

Figure 4.3

Comparison of intensity levels (median & Q1 – Q3) at different loudness levels using own prescribed hearing aids, 'test hearing aids' with linear setting, and 'test hearing aids' with non-linear setting.



Note. * = $p < 0.05$, measured using Friedman test.

Table 4.7

Significance of difference in intensity levels to identify specific loudness, measured using Friedman tests across three different conditions of hearing aids

Stimuli	Loudness level	*df*	*n*	*Chi-Square* (χ^2)	*p*	BF_{10}
500 Hz	Very soft	2	8	1.93	0.38	0.59
	Soft	2	13	1.19	0.55	0.24
	Comfortable	2	13	4.04	0.13	1.03
	Loud	2	8	11.08	0.004**	12.17
	Too loud	--$^{\#}$	--$^{\#}$	--$^{\#}$	--$^{\#}$	--$^{\#}$
1000 Hz	Very soft	2	7	6.46	0.04*	2.83
	Soft	2	13	6.39	0.41*	8.26
	Comfortable	2	13	9.70	0.01*	31.82
	Loud	2	8	7.16	0.03*	6.77
	Too loud	--$^{\#}$	--$^{\#}$	--$^{\#}$	--$^{\#}$	--$^{\#}$
4000 Hz	Very soft	2	7	5.30	0.07	1.20
	Soft	2	13	10.41	0.005*	14.10
	Comfortable	2	13	2.13	0.34	0.45
	Loud	2	9	2.97	0.23	0.50
	Too loud	--$^{\#}$	--$^{\#}$	--$^{\#}$	--$^{\#}$	--$^{\#}$
/u/	Very soft	2	7	11.08	0.004**	7.52
	Soft	2	13	0.56	0.75	0.26
	Comfortable	2	13	1.76	0.42	0.36
	Loud	2	8	2.15	0.34	0.29
	Too loud	--$^{\#}$	--$^{\#}$	--$^{\#}$	--$^{\#}$	--$^{\#}$
/a/	Very soft	2	6	2.82	0.24	0.77
	Soft	2	13	1.44	0.49	0.24
	Comfortable	2	13	9.70	0.008*	51.07
	Loud	2	10	9.95	0.007*	4.40
	Too loud	--$^{\#}$	--$^{\#}$	--$^{\#}$	--$^{\#}$	--$^{\#}$
/i/	Very soft	2	6	3.39	0.18	0.91
	Soft	2	13	2.28	0.32	0.29
	Comfortable	2	13	2.77	0.25	0.35
	Loud	2	13	4.55	0.10	0.79
	Too loud	--$^{\#}$	--$^{\#}$	--$^{\#}$	--$^{\#}$	--$^{\#}$

Note. * = $p < 0.05$; ** = $p < 0.01$; $^{\#}$ = not measured as very few participants chose the loudness level; BF_{10} = Bayes factor favouring the alternate hypothesis.

Table 4.8

Comparison of intensity levels to identify specific loudness between pairs of the three different conditions (own prescribed, linear, & non-linear), measured using Wilcoxon signed-rank tests.

Stimuli	**Loudness level**	**Hearing aid conditions**	**Median (Q1 – Q3)**	**Wilcoxon signed-rank results**			***BF_{10}***
				Z	***p***	***r***	
500 Hz	Loud	Own	85 (81.25 - 90)	-2.22	0.03	-0.70	1.36
		Linear	88.75 (84.38 - 92.5)				
		Own	85 (81.25 - 90)	-2.2	0.03	-0.73	3.13
		Non-linear	92.5 (87.5 - 95)				
		Linear	88.75 (84.38 - 92.5)	-1.93	0.05	-0.68	0.76
		Non-linear	92.5 (87.5 - 95)				
1000 Hz	Very soft	Own	37.5 (30 - 41.25)	-1.76	0.08	-0.62	0.67
		Linear	40 (33.75 - 43.12)				
		Own	37.5 (30 - 41.25)	-2.20	0.03	-0.83	1.98
		Non-linear	41.25 (31.88 – 48.75)				
		Linear	40 (33.75 - 43.12)	-1.06	0.29	-0.37	0.30
		Non-linear	41.25 (31.88 - 48.75)				
	Soft	Own	50 (46.25 - 55)	-0.36	0.72	-0.10	0.20
		Linear	52.5 (47.5 - 55)				
		Own	50 (46.25 - 55)	-2.25	0.02	-0.62	2.24
		Non-linear	55 (48.13 - 66.25)				
		Linear	52.5 (47.5 - 55)	-2.25	0.02	-0.62	1.63
		Non-linear	55 (48.13 - 66.25)				
	Comfortable	Own	67.5 (63.75 - 70)	-0.05	0.96	-0.01	0.16
		Linear	65 (60 - 77.5)				
		Own	67.5 (63.75 - 70)	-2.52	0.012*	-0.70	3.62
		Non-linear	75				

			(72.5 - 89.38)				
		Linear	65 (60 - 77.5)	-2.68	0.007*	-0.74	5.51
		Non-linear	75 (72.5 - 89.38)				
	Loud	Own	85 (83.75 - 88.75)	-0.43	0.66	-0.12	0.47
		Linear	85 (77.5 - 92.5)				
		Own	85 (83.75 - 88.75)	-1.53	0.12	-0.54	0.57
		Non-linear	93.75 (88.125 - 97.5)				
		Linear	85 (77.5 - 92.5)	-2.55	0.011*	-0.90	2.15
		Non-linear	93.75 (88.125 - 97.5)				
4000 Hz	Soft	Own	57.5 (53.75 - 63.75)	-2.59	0.010*	-0.72	5.97
		Linear	55 (50 - 65)				
		Own	57.5 (53.75 - 63.75)	-0.66	0.51	-0.18	0.25
		Non-linear	48.75 (45 - 55)				
		Linear	55 (50 - 65)	-2.19	0.03	-0.61	2.01
		Non-linear	48.75 (45 - 55)				
/u/	Very soft	Own	42.5 (36.25 - 45)	-0.21	0.83	-0.07	0.26
		Linear	42.5 (32.5 - 45)				
		Own	42.5 (36.25 - 45)	-2.38	0.017	-0.90	6.18
		Non-linear	32.5 (27.5 - 37.5)				
		Linear	42.5 (32.5 - 45)	-2.23	0.03	-0.84	5.60
		Non-linear	32.5 (27.5 - 37.5)				
/a/	Comfortable	Own	62.5 (60 - 67.5)	-0.51	0.96	-0.14	0.16
		Linear	62.5 (61.25 - 66.25)				
		Own	62.5 (60 - 67.5)	-2.65	0.008*	-0.73	7.19
		Non-linear	70 (65 - 72.5)				
		Linear	62.5 (61.25 - 66.25)	-2.56	0.01*	-0.71	7.19
		Non-linear	70 (65 - 72.5)				
	Loud	Own	80 (77.5 - 85)	0.00	1	0	0.18
		Linear	80 (80 - 82.5)				
		Own	80	-2.72	0.007*	-0.75	

		(77.5 - 85)				13.54
	Non-linear	85 (81.88 - 85.63)				
	Linear	80 (80 - 82.5)	-2.09	0.04	-0.58	1.02
	Non-linear	85 (81.88 - 85.63)				

Note. Q1 – Q3 = 25th percentile – 75th percentile; * = $p < 0.0167$; *r* (effect size) = $z/\sqrt{n}$; BF_{10} = Bayes factor favouring alternate hypothesis

For the hearing aids conditions that had a significant difference in the Friedman's test, a Wilcoxon signed-rank test was done. This was done to determine which of the three hearing aid conditions differed from each other (Table 4.8). A significant difference was mainly seen between the non-linear hearing aids and the linear hearing aids as well as between the performance on the participants' own prescribed hearing aids and the non-linear hearing aids. Additionally, the higher values of the Bayes factor (Table 4.8) confirmed that the conditions were significantly different.

4.2.2 Comparison of Intensity Discrimination across Three Different Device-Conditions in Children Using Hearing Aids.

The mean, standard deviation (SD), median, as well the 25th and 75th percentile of the intensity discrimination thresholds measured on the 20 hearing aid users are provided in Table 4.9 for the three device conditions. The hearing aid conditions included the participant's own prescribed hearing aids, 'test hearing aids' with a linear setting, and 'test hearing aids' with a non-linear setting. Figure 4.4 depicts a boxplot of the median and 25th and 75th percentile of the intensity discrimination thresholds for the three device conditions. As can be seen in Table 4.9 and Figure 4.4, the discrimination thresholds differed across the three hearing aid conditions, with the median being the lowest in the linear settings for most stimuli. An exception was 1000 Hz, where the thresholds obtained with the children using their own prescribed hearing aids were similar to that got through linear hearing aids, but were larger than that obtained through the non-linear hearing aids. The thresholds were the poorest for the non-linear settings for all stimuli.

Table 4.9

Mean and median with standard deviation (SD) and 25th - 75th percentile (Q1 - Q3) in parenthesis, and significance of difference for intensity discrimination thresholds (dB HL) for the three conditions in children using hearing aids (n = 20).

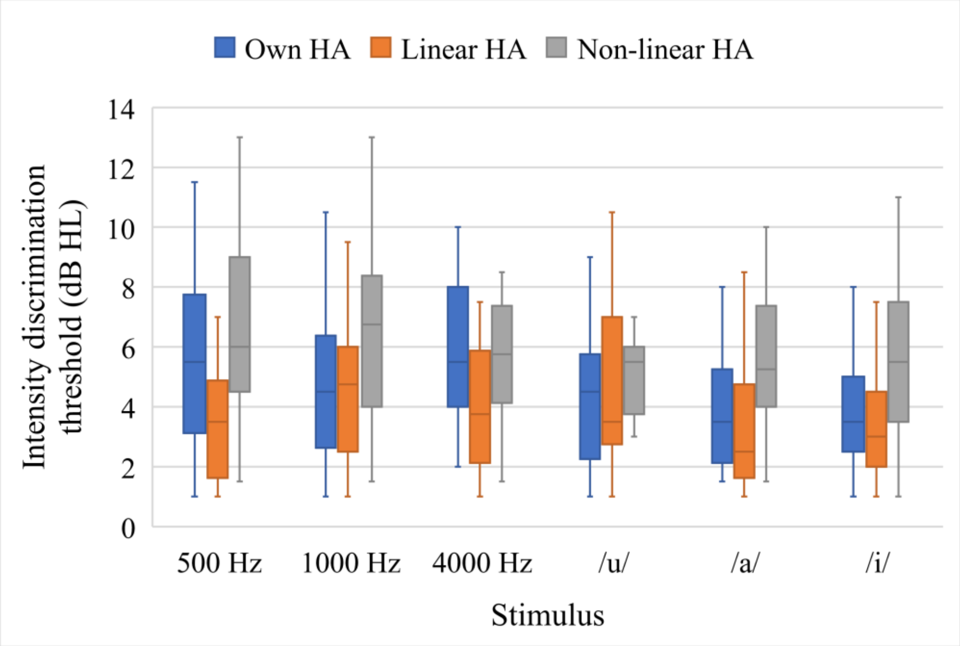
Stimuli	**Hearing Aid Conditions**						**Friedman test findings**			
	Own		**Linear**		**Non-linear**					
	Mean (SD)	**Median (Q1 – Q3)**	**Mean (SD)**	**Median (Q1 – Q3)**	**Mean (SD)**	**Median (Q1 – Q3)**	***df***	χ^2	***p***	BF_{10}
500 Hz	5.45 (2.92)	5.5 (3.13 - 7.75)	3.52 (1.92)	3.5 (1.63 - 4.88)	6.70 (3.20)	6 (4.5 - 9)	2	13.81	.001**	150.33
1000 Hz	4.82 (2.90)	4.5 (2.63 - 6.38)	4.57 (2.26)	4.75 (2.5 - 6)	6.57 (3.00)	6.75 (4 - 8.38)	2	9.02	.01*	5.27
4000 Hz	5.87 (2.28)	5.5 (4 - 8)	4.07 (2.15)	3.75 (2.13 - 5.88)	5.62 (2.01)	5.75 (4.13 - 7.38)	2	9.84	.007**	9.75
/u/	4.05 (2.01)	4.25 (2.13 - 5.25)	4.30 (2.48)	3.5 (2.62 - 6.25)	5.42 (2.56)	4.75 (3.63 - 6)	2	3.64	.16	0.89
/a/	3.97 (2.10)	3.5 (2.13 - 5.25)	3.52 (2.58)	2.5 (1.63 - 4.75)	5.35 (2.36)	5.25 (4 - 7.38)	2	5.25	.07	6.67
/i/	4.07 (2.22)	3.5 (2.63 - 5.38)	3.72 (2.34)	3 (2.13 - 5.25)	6.05 (2.88)	6 (3.63 - 7.88)	2	9.58	.008**	51.48

Note. * = $p < 0.05$; ** = $p < 0.01$; BF_{10} = Bayes factor favouring the alternate hypothesis.

To confirm if the differences were statistically different, the intensity discrimination thresholds obtained with the three hearing aid conditions were evaluated using Friedman's test (Table 4.9). Significant differences were observed between the three hearing aid conditions for 500 Hz, 1000 Hz, 4000 Hz warble-tones and vowel /i/. Further, Wilcoxon signed-rank test was done to establish which of the hearing aid conditions differed from each other (Table 4.10). As seen in the table, there was a significant difference between the linear settings and the non-linear settings for all stimuli. On the other hand, the participants' own prescribed hearing aids differed from either the linear or the non-linear hearing aids. The higher values of Bayes factor also confirmed the presence of the differences.

Figure 4.4

Boxplots comparing intensity discrimination thresholds in children using their own prescribed hearing aids, and 'test hearing aids' in linear and non-linear settings.



Note. HA = hearing aids

Table 4.10

Comparison of intensity discrimination thresholds between three different pairs of hearing aid conditions (own, linear & non-linear), measured using Wilcoxon signed-rank tests (n = 20)

Stimuli	**Hearing aid conditions**	**Median (Q1 – Q3)**	**Wilcoxon signed-rank results**			***BF*$_{10}$**
			Z	***p***	***r***	
500 Hz	Own	5.5 (3.13 - 7.75)	-2.56	0.01*	-0.57	3.72
	Linear	3.5 (1.63 - 4.88)				
	Own	5.5 (3.13 - 7.75)	-1.7	0.09	-0.38	0.47
	Non-linear	6 (4.5 - 9)				

	Linear	3.5 (1.63 - 4.88)	-3.15	0.002**	-0.70	43.73
	Non-linear	6 (4.5 - 9)				
1000 Hz	Own	4.5 (2.63 - 6.38)	-0.63	0.53	-0.14	0.15
	Linear	4.75 (2.5 - 6)				
	Own	4.5 (2.63 - 6.38)	-1.97	0.05	-0.44	1.04
	Non-linear	6.75 (4 - 8.38)				
	Linear	4.75 (2.5 - 6)	-2.56	0.01*	-0.57	5.54
	Non-linear	6.75 (4 - 8.38)				
4000 Hz	Own	5.5 (4 - 8)	-2.79	0.005**	-0.62	11.15
	Linear	3.75 (2.13 - 5.88)				
	Own	5.5 (4 - 8)	-0.38	0.70	-0.08	0.15
	Non-linear	5.75 (4.13 - 7.38)				
	Linear	3.75 (2.13 - 5.88)	-2.44	0.015*	-0.55	5.95
	Non-linear	5.75 (4.13 - 7.38)				
/i/	Own	3.5 (2.63 - 5.38)	-0.66	0.51	-0.15	0.32
	Linear	3 (2.13 - 5.25)				
	Own	3.5 (2.63 - 5.38)	-2.33	0.02	-0.52	4.40
	Non-linear	6 (3.63 - 7.88)				
	Linear	3 (2.13 - 5.25)	-3.05	0.002**	-0.68	23.90
	Non-linear	6 (3.63 - 7.88)				

Note. * = $p < 0.0167$; ** = $p < 0.01$; r (effect size) = $z/\sqrt{n}$; BF_{10} = Bayes factor favouring the alternate hypothesis.

From the comparisons of the three hearing aid conditions regarding the loudness identification, no specific trend was observable. Significant differences were observed between the conditions for a few stimuli for different loudness levels. On the other hand, for the intensity discrimination evaluation there was a significant difference between the linear and non-linear hearing aids settings for most of the stimuli, with it not being seen for the vowels /u/ and /a/. The difference was also noted between own-prescribed hearing aids and linear hearing settings for low and high frequency warble-tones. However, the intensity discrimination thresholds between the children’s own prescribed hearing aids was not significantly different with the non-linear hearing settings.

4.3 Comparison of Intensity Required to Identify Loudness Levels between the Participant Groups

Comparison of the three groups of participants (typically developing children, children using cochlear implants, & children using hearing aids) was done to establish the difference in intensity required to identify different loudness levels. This comparison was done thrice, with the typically developing children and children using cochlear implants being constant in all three statistical evaluations. However, the children using hearing aids were compared with the other two groups with them first wearing their own prescribed hearing aids, and then with them using the ‘test hearing aids’ with linear setting and ‘test hearing aids’ with non-linear setting. These comparisons were done using the random order method of stimulus presentation.

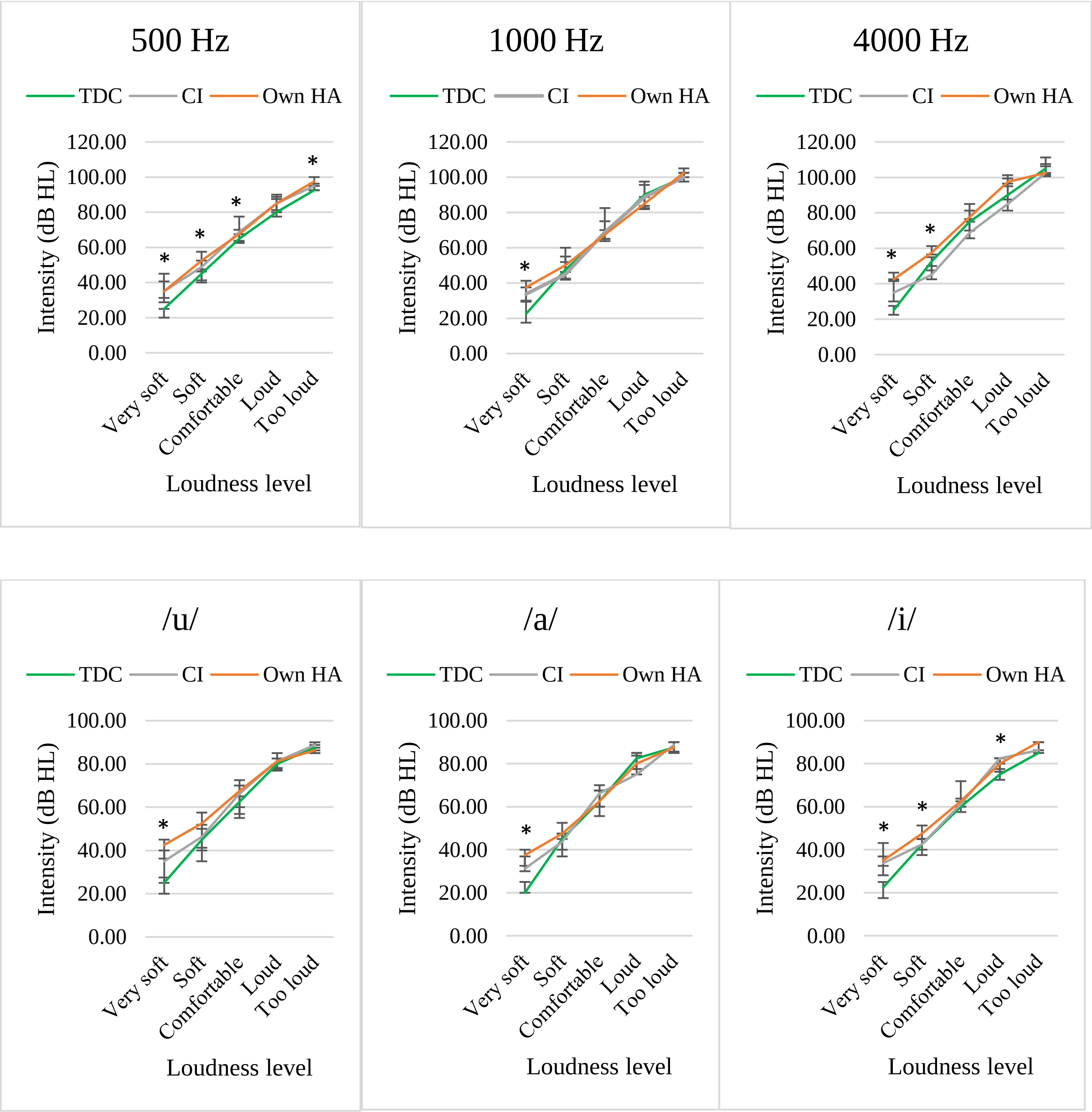
4.3.1 Comparison of Intensity Required to Identify Loudness Levels between the Typically Developing Children, Children Using Cochlear Implants and Children Using their Own Prescribed Hearing Aids.

The median, 25th and 75th percentile for the intensity required to perceive for each loudness level for the three participant groups (typically developing children, children using cochlear implants, & children using their own prescribed hearing aids) are depicted in Figure 4.5. In addition, the information is also provided in Table 4.1 and Table 4.2 (for typically developing children), Table 4.3 and Table 4.4 (for children using cochlear implants), as well as Table 4.5 & Table 4.6 (for children using hearing aids) along with the mean, standard deviation. Noticeable differences between the three groups can be observed for all the stimuli, mainly for the softer stimuli. In general, the children wearing their own prescribed hearing aids required higher intensities to perceive a particular loudness level when compared to the typically developing children and the children using cochlear implants. This trend was more prominent at the lower loudness levels for all stimuli except the 4000 Hz warble-tone, where this higher intensity was required for most loudness levels.

Kruskal-Wallis test, done to check if a significant difference was present between the three participant groups, revealed the presence of statistically significant differences at the 'very soft' level for all stimuli, and the 'soft' level for 500 Hz, 4000 Hz and /i/ (Table 4.11 & Table 4.12). Also, differences were noted for the 'comfortable' level for 500 Hz and the 'loud' and 'too loud' levels for the vowel /i/ and warble-tone of 500 Hz, respectively. To confirm which participant groups differed from each other, Mann-Whitney U test was done (Table 4.13, Table 4.14 & Table 4.15).

Figure 4.5

Comparison of intensity levels (median & Q1 – Q3) at different loudness levels between typically developing children (TDC), children using cochlear implants (CI), and children using their own prescribed hearing aids (HA).



Note. * = $p < 0.05$, measured using Kruskal-Wallis test

Table 4.11

Significance of difference of intensity required to identify loudness levels of warble-tones, measured using Kruskal-Wallis test, across the three participant groups (typically developing children, children using cochlear implants, & children using their own prescribed hearing aids)

Loudness level	**Stimuli**											
	500 Hz				**1000 Hz**				**4000 Hz**			
	df	χ^2	***p***	BF_{10}	***df***	χ^2	***p***	BF_{10}	***df***	χ^2	***p***	BF_{10}
VS	2	28.24	< 0.001***	1.65×10^8	2	28.10	< 0.001***	1.008×10^7	2	25.86	< 0.001***	1.566×10^6
S	2	9.42	0.009**	10.10	2	2.94	0.23	0.42	2	14.42	0.001**	16.83
C	2	8.31	0.02*	7.61	2	0.75	0.69	0.19	2	1.80	0.41	0.37
L	2	3.98	0.14	0.67	2	1.07	0.59	0.26	2	4.69	0.10	1.39
TL	2	9.30	0.01*	7.47	2	1.12	0.57	0.30	2	0.62	0.73	0.28

Note. VS = Very soft; S = Soft; C = Comfortable; L = Loud; TL = Too loud; * = $p < 0.05$; ** = $p < 0.01$; *** = $p < 0.001$; BF_{10} = Bayes factor favouring the alternate hypothesis

Table 4.12

Significance of difference of intensity required to identify loudness levels of vowels, measured using Kruskal-Wallis test, across the three participant groups (typically developing children, children using cochlear implants, & children using their own prescribed hearing aids)

Loudness level	**Stimuli**											
	/u/				**/a/**				**/i/**			
	df	χ^2	***p***	BF_{10}	***df***	χ^2	***p***	BF_{10}	***df***	χ^2	***p***	BF_{10}
VS	2	28.8	< 0.001***	1.466×10^8	2	25.77	< 0.001**	860518.21	2	26.88	< 0.001***	5.6111466×10^6
S	2	5.11	0.08	2.06	2	3.64	0.16	0.53	2	8.38	0.01*	1.56
C	2	3.01	0.22	0.53	2	0.34	0.84	0.46	2	1.79	0.41	0.46
L	2	0.75	0.69	0.21	2	0.95	0.62	3.6	2	6.59	0.04*	3.6
TL	2	1.4	0.5	0.49	2	0.18	0.91	1.13	2	4.74	0.09	1.13

Note. VS = Very soft; S = Soft; C = Comfortable; L = Loud; TL = Too loud; * = $p < 0.05$; ** = $p < 0.01$; *** = $p < 0.001$; BF_{10} = Bayes factor favouring the alternate hypothesis

Table 4.13

Comparison of intensity (dB HL) required to identify loudness levels by typically developing children (TDC) with children using cochlear implants (CI) measured using Mann-Whitney U test.

Stimuli	***Loudness levels***	***Groups***	***Median (Q1 – Q3)***	***Mann-Whitney U results***			BF_{10}
				U	***p***	***r***	
500 Hz	VS	TDC	25 (20 - 25)	30.50	< 0.001**	-0.60	12483.61
		CI	35 (28.75 - 40.63)				
	S	TDC	45 (40 - 47.5)	131.50	0.14	-0.23	0.44
		CI	48.75 (41.25 - 52.5)				
	C	TDC	65 (62.5 - 67.5)	104.50	0.03	-0.34	4.82
		CI	68.75 (63.13 - 77.5)				
	TL	TDC	92.5 (92.5 - 95)	52.00	0.34	-0.18	0.32
		CI	95 (92.5 - 96.25)				
1000 Hz	VS	TDC	22.5 (17.5 - 25.62)	15.00	< 0.001**	-0.67	24577.95
		CI	33.75 (29.38 - 37.5)				
4000 Hz	VS	TDC	25 (22.5 - 27.5)	25.00	< 0.001**	-0.62	122.56
		CI	35 (30 - 37.5)				
	S	TDC	52.5 (47.5 - 55)	87.50	0.007*	-0.41	1.58
		CI	45 (42.5 - 47.5)				
/u/	VS	TDC	25 (20 - 27.5)	13.50	< 0.001**	-0.63	2428.30
		CI	35 (30 - 40)				
/a/	VS	TDC	20 (20 - 25)	11.50	< 0.001**	-0.63	2223.24
		CI	31.25 (30 - 36.88)				
/i/	VS	TDC	22.5 (17.5 - 25)	9.50	< 0.001**	-0.65	7969.64
		CI	33.75				

		(28.13 - 36.88)				
S	TDC	42.5 (37.5 - 45)	161.00	0.49	-0.11	0.34
	CI	42.5 (40 - 45)				
L	TDC	75 (72.5 - 80)	80.00	0.08	-0.29	0.73
	CI	82.5 (76.25 - 82.5)				

Note. * = $p < 0.0167$; ** = $p < 0.001$; r (effect size) = $z/\sqrt{n}$; BF_{10} = Bayes factor in favour of the alternate hypothesis; VS = Very soft; S = Soft; C = Comfortable; L = Loud; TL = Too loud.

From Table 4.13 it can be observed that the intensity levels to identify specific loudness differed significantly between the typically developing children and the children using cochlear implants only at the ‘very soft’ loudness levels. This was observed for all six stimuli that were studied. Additionally, for the 4000 Hz warble-tone the difference was also noted for the ‘soft’ loudness level.

Likewise, the comparison between the typically developing children and the children using their own prescribed hearing aids revealed a statistically significant difference for the ‘very soft’ loudness level for all the stimuli (Table 4.14). Significant differences were also observed for a few stimuli for the ‘soft’ and ‘too loud’ loudness levels. The high values of Bayes factor confirmed the presence of the significant difference.

The comparison between the children using cochlear implants and the children using their own prescribed hearing aids revealed significant differences at the ‘very soft’ and ‘soft’ levels of loudness for the 4000 Hz warble-tone (Table 4.15). The performance for all other stimuli at each loudness level was similar between the two groups.

Table 4.14

Comparison of intensity (dB HL) required to identify loudness levels by typically developing children (TDC) with children using their own prescribed hearing aids (HA-OP), evaluated using Mann-Whitney U test.

Stimuli	***Loudness levels***	***Groups***	***Median (Q1 – Q3)***	***Mann-Whitney U results***			***BF*** $_{10}$
				U	***p***	***r***	
500 Hz	VS	TDC	25 (20 - 25)	3.50	< 0.001**	-0.71	1.301×10^{6}
		HA-OP	35 (31.25 - 45)				
	S	TDC	45 (40 - 47.5)	87.50	0.003*	-0.45	18.50
		HA-OP	52.5 (46.25 - 57.5)				
	C	TDC	65 (62.5 - 67.5)	100.50	0.02	-0.36	1.56
		HA-OP	67.5 (63.75 - 70)				
	TL	TDC	92.5 (92.5 - 95)	29.00	0.003*	-0.53	8.89
		HA-OP	97.5 (95 - 100)				
1000 Hz	VS	TDC	22.5 (17.5 - 25.62)	14.00	< 0.001**	-0.65	113937.27
		HA-OP	37.5 (30 - 41.25)				
4000 Hz	VS	TDC	25 (22.5 - 27.5)	22.00	< 0.001**	-0.61	84460.90
		HA-OP	42.5 (38.75 - 51.25)				
	S	TDC	52.5 (47.5 - 55)	108.50	0.016*	-0.36	1.23
		HA-OP	57.5 (53.75 - 63.75)				
/u/	VS	TDC	25 (20 - 27.5)	3.50	< 0.001**	-0.71	1.672×10^{7}
		HA-OP	42.5 (36.25- 45)				
/a/	VS	TDC	20 (20 - 25)	31.00	< 0.001**	-0.62	47888.48
		HA-OP	37.5 (32.5-40)				
/i/	VS	TDC	22.5 (17.5 - 25)	18.50	< 0.001**	-0.65	201214.88
		HA-OP	35 (32.5- 43.13)				

S	TDC	42.5 (37.5 - 45)	93.50	0.005*	-0.43	1.69
	HA-OP	47.5 (45- 51.25)				
L	TDC	75 (72.5 - 80)	106.00	0.03	-0.35	2.38
	HA-OP	80 (77.5- 82.5)				

Note. * = $p < 0.0167$; ** = $p < 0.001$; r (effect size) = $z/\sqrt{n}$; BF_{10} = Bayes factor in favour of the alternate hypothesis; VS = Very soft; S = Soft; C = Comfortable; L = Loud; TL = Too loud.

Table 4.15

Comparison of intensity (dB HL) required to identify loudness levels by children using cochlear implants (CI) with children using their own prescribed hearing aids (HA-OP) evaluated using Mann-Whitney U test.

Stimuli	***Loudness levels***	***Groups***	***Median (Q1 – Q3)***	***Mann-Whitney U results***			***BF_{10}***
				U	***p***	***r***	
500 Hz	VS	CI	35 (28.75 - 40.63)	32.50	0.30	-0.24	0.40
		HA-OP	35 (31.25 - 45)				
	C	CI	68.75 (63.13 - 77.5)	53.50	0.18	-0.27	0.45
		HA-OP	67.5 (63.75 - 70)				
	L	CI	85 (80 - 88.75)	59.00	0.45	-0.16	0.28
		HA-OP	85 (81.25 - 90)				
	TL	CI	95 (92.5 - 96.25)	11.00	0.08	-0.47	0.74
		HA-OP	97.5 (95 - 100)				
1000 Hz	VS	CI	33.75 (29.38 - 37.5)	32.00	0.29	-0.25	0.35
		HA-OP	37.5 (30 - 41.25)				
4000 Hz	VS	CI	35 (30 - 37.5)	11.50	0.006*	-0.64	2.49
		HA-OP	42.5 (38.75 - 51.25)				
	S	CI	45 (42.5 - 47.5)	20.00	0.002*	-0.63	13.99
		HA-OP	57.5				

			(53.75 - 63.75)				
/u/	VS	CI	35 (30 - 40)	18.50	0.09	-0.41	0.71
		HA-OP	42.5 (36.25- 45)				
/a/	VS	CI	31.25 (30 - 36.88)	26.50	0.14	-0.33	0.33
		HA-OP	37.5 (32.5-40)				
/i/	VS	CI	33.75 (28.13 - 36.88)	29.00	0.32	-0.23	0.29
		HA-OP	35 (32.5- 43.13)				
	S	CI	42.5 (40 - 45)	42.50	0.05	-0.39	0.32
		HA-OP	47.5 (45- 51.25)				
	L	CI	82.5 (76.25 - 82.5)	53.00	0.70	-0.08	0.23
		HA-OP	80 (77.5- 82.5)				

Note. * = $p < 0.0167$; ** = $p < 0.001$; r (effect size) = $z/\sqrt{n}$; BF_{10} = Bayes factor favouring the alternate hypothesis; VS = Very soft; S = Soft; C = Comfortable; L = Loud; TL = Too loud.

Additionally, *canonical discriminant analysis* was also conducted to determine the stimuli and its discriminant coefficient / relative weightage that differentiated the three groups from each other. This was done as Kruskal-Wallis test and Mann-Whitney U differentiated pairs of participant groups and did not specify which particular variable differentiated one group from the other group. The analysis was done after excluding the two extreme loudness levels as only a limited number of participants perceived the stimuli as being ‘very soft’ or ‘too loud’. Missing intensity data in the ‘soft’, ‘comfortable’, and ‘loud’ levels were replaced by the mean data of that particular group. Parametric discriminant analysis was done as the mean, median and mode intensity values of the three loudness levels was less than 5 dB for majority of the variables (93%) in all three groups (Tables 4.1, 4.2, 4.3, 4.4, 4.5 & 4.6), indicating Gaussian distribution (Ahsanullah et al., 2014; Remington & Schork, 1970). A difference of 5 dB is considered as acceptable test-retest variability (Carhart & Jerger, 1959; Sherlock & Formby, 2005).

Two discriminant functions were obtained with them having eigen values of 1.10 and 0.74. These two functions (F1 & F2) accounted for 59.8% and 40.2% of the variance respectively. Wilk's lambda for the two functions ($\lambda = 0.27$, $p = 0.01$) indicated that mean scores were significantly different between the three groups. Details of the two functions and their structure coefficients are provided in Table 4.16. The discriminant function differentiated 80.6% of the typically developing children, 58.3% of the children using cochlear implants and 92.3% of the children using their own prescribed hearing aids. When the three participant groups were combined, 78.6% of them were correctly classified. Three of the typically developing children were misclassified as children using cochlear implants and another three of them were misclassified as children using hearing aids. Likewise, three of the children using cochlear implants were misclassified as typically developing children and two of them were misclassified as children using hearing aids. Only one child using hearing aids was misclassified as typically developing children. Further, a canonical score plot (Figure 4.6) was constructed using Systat, Version 13.2 (Systat Software, Inc.). The plot depicts the difference between the three groups for the two functions based on the canonical scores of predictor variables.

It is evident from Figure 4.6 that Function 1 majorly differentiated between the typically developing children and the children using cochlear implants. They were mainly differentiated by four predictor variables ('/i/, loud', '500 Hz, comfortable', '4000 Hz, soft', & '/i/, comfortable'), based on the standardised discriminant function coefficients (Table 4.16). On the other hand, Function 2 mainly separated the two clinical groups, although the functions overlapped between the groups (Figure 4.6). The groups were differentiated mainly by the stimulus '4000 Hz, soft', followed by '500 Hz, soft', '500 Hz, comfortable' and '1000 Hz, loud' (Table 4.16). The variables in Function 2 had relatively higher weightage compared to that seen in Function 1.

Table 4.16

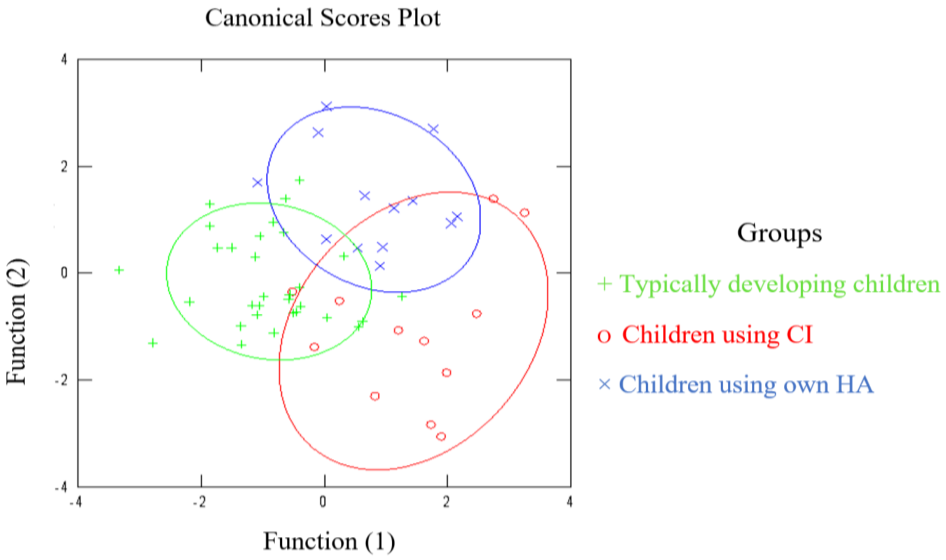
Standardised discriminant function, structure canonical coefficients and effect size for each predictor variable to discriminate the typically developing children, children using cochlear implants, and children using their own prescribed hearing aids.

Variables		Function 1			Function 2		
		Standardised discriminant function coefficients	**Structure canonical coefficients *(r)***	**Effect size *(r^2)***	**Standardised discriminant function coefficients**	**Structure canonical coefficients *(r)***	**Effect size *(r^2)***
500 Hz	S	0.01	0.35	0.12	0.94	0.35	0.12
	C	0.84	0.43	0.18	-0.89	-0.06	0.00
	L	0.23	0.27	0.07	0.52	0.89	0.79
1000 Hz	S	0.54	0.009	0.00	-0.52	0.24	0.06
	C	-0.57	0.01	0.00	0.46	-0.13	0.02
	L	0.00	0.001	0.00	-0.65	-0.20	0.04
4000 Hz	S	-0.74	-0.09	0.01	0.99	0.60	0.36
	C	0.39	0.009	0.00	-0.39	0.26	0.07
	L	-0.43	-0.02	0.00	0.42	0.49	0.24
/u/	S	0.36	0.27	0.07	-0.42	0.27	0.07
	C	-0.07	0.23	0.05	0.53	-0.06	0.00
	L	-0.39	0.10	0.01	-0.45	0.03	0.00
/a/	S	-0.41	0.02	0.00	-0.18	0.30	0.09
	C	-0.43	-0.12	0.01	0.48	-0.007	0.00
	L	0.26	-0.14	0.02	-0.22	0.04	0.00
/i/	S	0.69	0.27	0.07	0.03	0.23	0.05
	C	-0.72	0.20	0.04	-0.54	-0.13	0.02
	L	0.91	0.40	0.16	0.58	0.15	0.02

Note. S = Soft; C = Comfortable; L = Loud.

Figure 4.6

Canonical scores plotted across the two discriminant functions for loudness growth identification in typically developing children, children using cochlear implants (CI) and children using own hearing aids (HA). The ellipses show 95% confidence boundaries of each group.

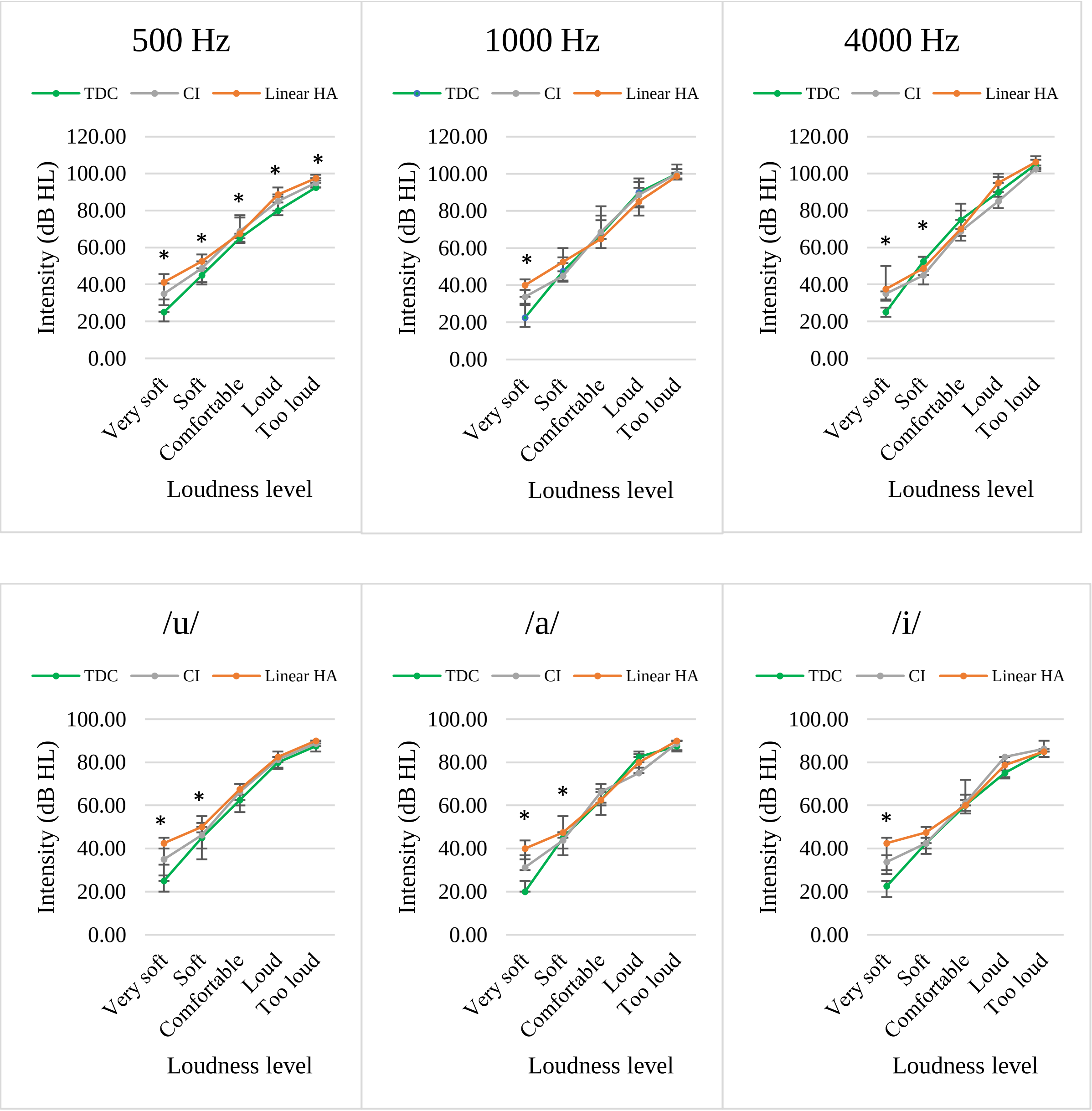


4.3.2 Comparison of Intensity Required to Identify Loudness Levels between Typically Developing Children, Children Using Cochlear Implants, and Children Using the 'Test Hearing Aids' in Linear Setting

The median, 25th and 75th percentile of the intensity (dB HL) required to perceive loudness levels indicated that there were differences in the values between the three groups (Figure 4.7). The three groups had similar responses for all stimuli except for the 'very soft' and 'soft' levels of loudness. At these two lower loudness levels, children using the 'test hearing aids' in a linear setting needed the highest intensity, followed by the children using cochlear implants. The typically developing children required the least intensity to perceive these two loudness levels. Kruskal-Wallis test was measured at each loudness level for each stimulus to confirm whether significant differences existed between the three groups (Table 4.17 & Table 4.18).

Figure 4.7

Comparison of intensity levels (median & Q1 – Q3) at different loudness levels between typically developing children (TDC), children using cochlear implants (CI) and children using hearing aids (HA) in linear setting.



Note. * = $p < 0.05$, measured using Kruskal-Wallis test.

Table 4.17

Significance of difference in intensity required to identify loudness levels of warble-tones, measured using Kruskal-Wallis test, across the three participant groups (typically developing children, children using cochlear implants, & children using 'test hearing aids' in linear setting)

Loudness level	**Stimuli**											
	500 Hz				**1000 Hz**				**4000 Hz**			
	df	χ^2	***p***	BF_{10}	***df***	χ^2	***p***	BF_{10}	***df***	χ^2	***p***	BF_{10}
VS	2	15.62	< 0.001***	10.34	2	33.27	< 0.001***	2.720×10^{9}	2	26.66	< 0.001***	117283.84
S	2	11.42	0.003**	5.68	2	4.66	0.10	0.71	2	7.25	0.03*	1.30
C	2	9.30	0.01*	13.74	2	0.86	0.65	0.17	2	1.29	0.57	0.26
L	2	7.61	0.02*	2.94	2	1.53	0.47	0.27	2	3.49	0.17	0.45
TL	2	7.70	0.02*	3.27	2	2.10	0.35	0.41	2	1.11	0.57	0.30

Note. VS = Very soft; S = Soft; C = Comfortable; L = Loud; TL = Too loud; * = $p < 0.05$; ** = $p < 0.01$; *** = $p < 0.001$; BF_{10} = Bayes factor favouring the alternate hypothesis

Table 4.18

Significance of difference in intensity required to identify loudness levels of vowels, measured using Kruskal-Wallis test, across the three participant groups (typically developing children, children using cochlear implants, & children using 'test hearing aids' in linear setting

Loudness level	**Stimuli**											
	/u/				**/a/**				**/i/**			
	df	χ^2	***p***	BF_{10}	***df***	χ^2	***p***	BF_{10}	***df***	χ^2	***p***	BF_{10}
VS	2	27.95	< 0.001***	2.218×10^{7}	2	29.32	< 0.001***	1.420×10^{8}	2	26.02	< 0.001***	9.963×10^{6}
S	2	9.62	0.008**	9.52	2	6.44	0.04*	1.39	2	4.49	0.11	0.78
C	2	4.91	0.09	1.12	2	0.42	0.81	0.22	2	2.35	0.31	0.46
L	2	2.29	0.32	0.45	2	1.06	0.59	0.24	2	3.29	0.19	0.51
TL	2	2.61	0.27	0.76	2	1.12	0.57	0.46	2	0.75	0.69	0.41

Note. VS = Very soft; S = Soft; C = Comfortable; L = Loud; TL = Too loud; * = $p < 0.05$; ** = $p < 0.01$; *** = $p < 0.001$; BF_{10} = Bayes factor favouring the alternate hypothesis

Table 4.19

Comparison of intensity (dB HL) required to identify loudness level by the typically developing children (TDC) with children using hearing aids in linear settings (HA-L), measured using Mann-Whitney U test

Stimuli	***Loudness level***	***Group***	***Median (Q1 – Q3)***	***Mann-Whitney U results***			***BF₁₀***
				U	***p***	***r***	
500 Hz	VS	TDC	25 (20 - 25)	105.50	0.012*	-0.38	0.96
		HA-L	41.25 (31.88 - 45.62)				
	S	TDC	45 (40 - 47.5)	73.00	< 0.001**	-0.50	8.59
		HA-L	52.5 (48.75 - 56.25)				
	C	TDC	65 (62.5 - 67.5)	100.50	0.008*	-0.40	10.85
		HA-L	67.5 (65 - 76.25)				
	L	TDC	80 (77.5 - 87.5)	66.00	0.008*	-0.42	3.49
		HA-L	88.75 (84.38 - 92.5)				
	TL	TDC	92.5 (92.5 - 95)	8.50	0.008*	-0.51	3.93
		HA-L	97.5 (97.5 - 99.38)				
1000 Hz	VS	TDC	22.5 (17.5 - 25.62)	1.00	< 0.001**	-0.74	7.36×10^7
		HA-L	40 (33.75 - 43.12)				
4000 Hz	VS	TDC	25 (22.5 - 27.5)	15.00	< 0.001**	-0.64	6775.32
		HA-L	37.5 (31.25 - 50)				
	S	TDC	52.5 (47.5 - 55)	150.00	0.33	-0.15	0.24
		HA-L	48.75 (45 - 55)				
/u/	VS	TDC	25 (20 - 27.5)	6.50	< 0.001**	-0.69	2.15×10^6
		HA-L	42.5 (32.5 - 45)				
	S	TDC	45 (40 - 47.5)	80.00	0.002*	-0.48	16.63
		HA-L	50 (47.5 - 55)				

/a/	VS	TDC	20 (20 - 25)	5.00	< 0.001**	-0.69	5.91×10^6
		HA-L	40 (35 - 43.75)				
	S	TDC	45 (40 - 47.5)	113.50	0.02	-0.35	1.51
		HA-L	47.5 (45 - 55)				
/i/	VS	TDC	22.5 (17.5 - 25)	5.50	< 0.001**	-0.64	253381.21
		HA-L	42.5 (30 - 45)				

Note. * = $p < 0.0167$; ** = $p < 0.001$; BF_{10} = Bayes factor favouring the alternate hypothesis; VS = Very soft; S = Soft; C = Comfortable; L = Loud; VL = Very loud.

The Kruskal-Wallis test indicated that there were significant differences in intensity at all loudness levels among the three groups for the 500 Hz warble-tone. For the 1000 Hz warble-tone and high frequency vowel /i/, there were significant differences in intensity level only at the ‘very soft’ level. However, for the 4000 Hz warble-tone and the vowels /a/ and /u/, there were significant differences at both ‘very soft’ and ‘soft’ levels. Thus, Mann-Whitney U tests were conducted for these stimuli. The results are provided only for the children using the ‘test hearing aids’ in linear setting with the other two groups. The results of the typically developing children and the children using cochlear implants are given earlier in section 4.3.1.

The Mann-Whitney U test (Table 4.19) indicated that the typically developing children required significantly lesser intensity than those using the ‘test hearing aids’ in linear setting for the 500 Hz warble-tone. This was seen at all the loudness levels. However, for a few of the other stimuli, there was a significant difference only for the ‘very soft’ and / or the ‘soft’ loudness levels. The higher Bayes factor values also confirmed that the difference was significant. On the other hand, between the children using cochlear implants and those using the ‘test hearing aids’ in linear setting, there was no statistically significant differences (Table 4.20).

Table 4.20

Comparison of intensity (dB HL) required to identify loudness levels by children using cochlear implants (CI) with children using hearing aids in linear settings (HA-L), measured using Mann-Whitney U test

Stimuli	***Loudness level***	***Group***	***Median (Q1 – Q3)***	***Mann-Whitney U results***			***BF_{10}***
				U	***p***	***r***	
500 Hz	Very soft	CI	35 (28.75 - 40.63)	62.00	0.85	-0.04	0.27
		HA-L	41.25 (31.88 - 45.62)				
	Soft	CI	48.75 (41.25 - 52.5)	51.50	0.15	-0.29	0.38
		HA-L	52.5 (48.75 - 56.25)				
	Comfortable	CI	68.75 (63.13 - 77.5)	74.50	0.85	-0.04	0.22
		HA-L	67.5 (65 - 76.25)				
	Loud	CI	85 (80 - 88.75)	25.00	0.18	-0.32	0.36
		HA-L	88.75 (84.38 - 92.5)				
	Too loud	CI	95 (92.5 - 96.25)	3.50	0.06	-0.59	0.91
		HA-L	97.5 (97.5 - 99.38)				
1000 Hz	Very soft	CI	33.75 (29.38 - 37.5)	19.50	0.02	-0.52	1.87
		HA-L	40 (33.75 - 43.125)				
4000 Hz	Very soft	CI	35 (30 - 37.5)	28.00	0.15	-0.33	0.93
		HA-L	37.5 (31.25 - 50)				
	Soft	CI	45 (42.5 - 47.5)	48.50	0.17	-0.28	0.49
		HA-L	48.75 (45 - 55)				
/u/	Very soft	CI	35 (30 - 40)	20.00	0.12	-0.38	0.54
		HA-L	42.5 (32.5 - 45)				
	Soft	CI	46.25 (40.63 - 51.83)	49.00	0.11	-0.32	0.59
		HA-L	50 (47.5 - 55)				

/a/	Very soft	CI	31.25 (30 - 36.88)	17.00	0.06	-0.45	0.97
		HA-L	40 (35 - 43.75)				
	Soft	CI	43.75 (36.88 - 47.5)	38.50	0.03	-0.44	1.34
		HA-L	47.5 (45 - 55)				
/i/	Very soft	CI	33.75 (28.13 - 36.88)	18.50	0.27	-0.29	0.45
		HA-L	42.5 (30 - 45)				

Note. * = $p < 0.0167$; ** = $p < 0.001$; BF_{10} = Bayes factor favouring the alternate hypothesis; VS = Very soft; S = Soft; C = Comfortable; L = Loud; TL = Too loud.

Canonical discriminant analysis was performed to determine the variables that differentiate the three participant groups (typically developing children, children using cochlear implants, & children using the 'test hearing aids' in linear setting). Two discriminant functions were obtained with eigen values of 2.14 and 0.59. These two functions accounted for 78.3% and 21.7% of the variances, respectively. A significant Wilk's lambda for functions 1 and 2 ($\lambda = .20$; $p < 0.001$) also indicated that means scores were significantly different between the three groups. The structure coefficients of each variable in the two functions are depicted in Table 4.21. Also, Figure 4.8 indicated the discrimination of the three groups based on the variables across the two functions. The discriminant function accurately classified 90.3% of the typically developing children, 83.3% of the children using cochlear implants and 76.9% of the children using 'test hearing aids' in linear setting. When the three participant groups were combined, the overall classification accuracy was 85.7%. Two of the typically developing children were misclassified as children using cochlear implants and one of them was misclassified along with children using hearing aids. Similarly, one child using a cochlear implant was misclassified as a typically developing child and another one as a child using hearing aids. Likewise, three children using hearing aids were misclassified as children using cochlear implants.

Table 4.21

Standardised discriminant function, structure canonical coefficients and effect size for each predictor variable to discriminate the typically developing children, children using cochlear implants and children using the 'test hearing aids' in linear setting.

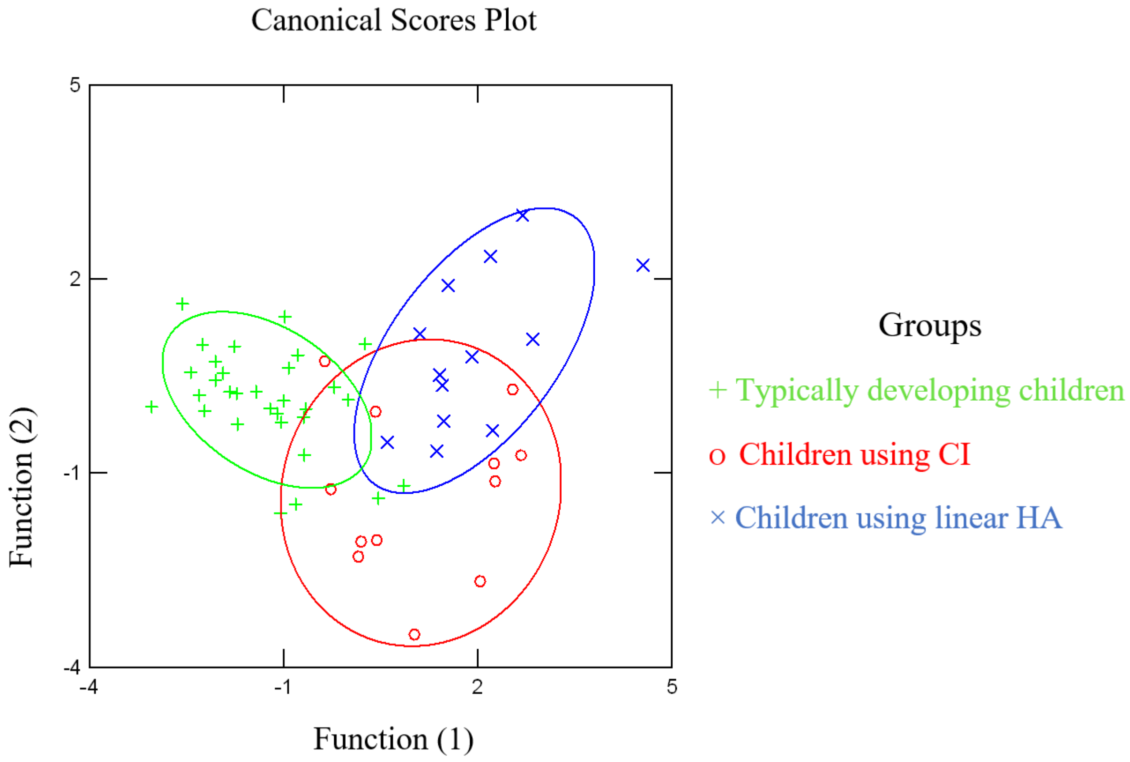
Variables		**Function 1**			**Function 2**		
		Standardised discriminant function coefficients	**Structure canonical coefficients** ***(r)***	**Effect size** ***(r^2)***	**Standardised discriminant function coefficients**	**Structure canonical coefficients** ***(r)***	**Effect size** ***(r^2)***
500 Hz	S	0.10	0.29	0.08	0.42	0.15	0.02
	C	0.37	0.33	0.11	-0.15	-0.05	0.00
	L	0.70	0.31	0.10	-0.02	0.12	0.01
1000 Hz	S	1.05	0.16	0.03	0.02	0.26	0.07
	C	-0.63	-0.01	0.00	0.01	-0.10	0.01
	L	-0.23	-0.06	0.00	-0.48	-0.21	0.04
4000 Hz	S	-1.36	-0.16	0.03	0.22	0.31	0.10
	C	0.48	-0.11	0.01	-0.86	-0.04	0.00
	L	-0.26	0.02	0.00	0.96	0.38	0.14
/u/	S	0.14	0.30	0.09	-0.10	0.20	0.04
	C	0.53	0.20	0.04	-0.73	-0.14	0.02
	L	0.03	0.16	0.03	0.87	0.11	0.01
/a/	S	-0.14	0.13	0.02	0.42	0.38	0.14
	C	-0.57	-0.08	0.01	0.29	0.06	0.00
	L	0.25	-0.06	0.00	-0.12	0.20	0.04
/i/	S	0.59	0.20	0.04	-0.46	0.03	0.00
	C	-0.70	0.05	0.00	0.51	-0.31	0.10
	L	0.24	0.15	0.02	-0.78	-0.26	0.07

Note. S = Soft; C = Comfortable; L = Loud.

Function 1 differentiated the typically developing children from those wearing linear hearing aids (Figure 4.8). The variables that mainly differentiated these two groups, as evident in Table 4.21, were ‘500 Hz, loud’, ‘/i/, comfortable’, ‘1000 Hz, comfortable’, ‘/i/, soft’, and ‘/a/, comfortable’. The groups that were predominately differentiated by Function 2 were the typically developing children from the children using cochlear implants (Figure 4.8). These groups were differentiated by ‘4000 Hz, loud’, ‘/u/, loud’, ‘4000 Hz, comfortable’, ‘/i/, loud’, and ‘/u/, comfortable’. The weightage provided by the variables in Function 2 was higher compared to Function 1.

Figure 4.8

Canonical scores plotted across the two discriminant functions for loudness growth identification in typically developing children, children using cochlear implants (CI) and children using ‘test hearing aids (HA)’ in linear setting. The ellipses show 95% confidence boundaries of each group.



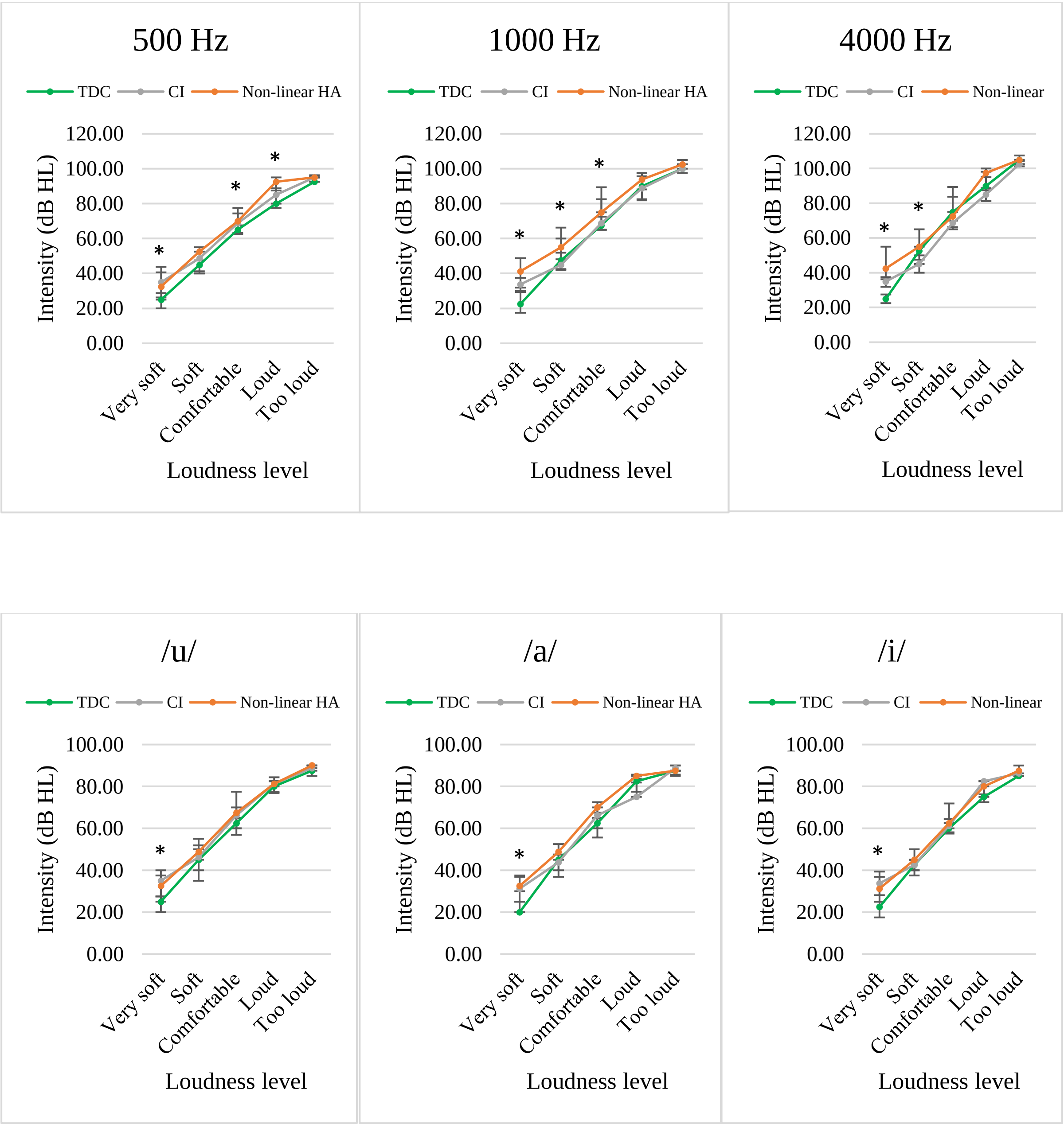
4.3.3 Comparison of Intensity Required to Identify Loudness Levels between the Typically Developing Children, Children Using Cochlear Implants and Children Using the 'Test Hearing Aids' in Non-Linear Setting

From the median, 25th and 75th percentile of the intensity levels required to identify specific loudness levels (Figure 4.9), it can be seen that there were differences between the three participant groups (typically developing children, children using cochlear implants, & children using the 'test hearing aids' in non-linear setting). The differences were more prominent for the warble-tones than the three vowels that were used. In general, the children using the non-liner 'test hearing aids' required higher intensity compared to the children using cochlear implants. Further, the latter group needed more intensity compared to the typically developing children. However, this varied depending on the stimuli and the loudness level.

Kruskal-Wallis test was done to confirm if statistical differences existed between the participant groups. The results indicated that there were statistically significant differences noted in intensity levels at 'very soft' levels for all the stimuli and 'soft' levels of 1000 Hz and 4000 Hz. Also, there were significant differences for the 'comfortable' levels of 500 Hz and 1000 Hz and 'loud' level of 500 Hz (Table 4.22 & Table 4.23). Thus, the Mann-Whitney U tests were done only for these loudness levels.

Figure 4.9

Comparison of intensity levels (median & Q1 – Q3) at different loudness levels between typically developing children (TDC), children using cochlear implants (CI) and children using hearing aids (HA) in non-linear setting.



Note. * = $p < 0.05$, measured using Kruskal-Wallis test.

Table 4.22

Significance of difference in intensity required to identify loudness levels of warble-tones, measured using Kruskal-Wallis test, across the three participant groups (typically developing children, children using cochlear implants, & children using the 'test hearing aids' in non-linear setting)

Loudness level	**Stimuli**											
	500 Hz				**1000 Hz**				**4000 Hz**			
	df	**χ^2**	***p***	**BF_{10}**	***df***	**χ^2**	***p***	**BF_{10}**	***df***	**χ^2**	***p***	**BF_{10}**
VS	2	15.99	< 0.001***	122.10	2	30.49	< 0.001***	2.856×10^8	2	27.68	< 0.001***	5.392×10^6
S	2	4.25	0.12	0.69	2	12.08	< 0.001*	91.53	2	11.15	< 0.001***	3.45
C	2	12.85	< 0.001***	43.13	2	8.34	0.02***	43.41	2	0.51	0.78	0.19
L	2	11.85	< 0.001***	32.71	2	3.33	0.19	0.61	2	4.48	0.11	0.83
TL	2	1.30	0.52	0.45	2	1.39	0.50	0.41	2	0.10	0.95	0.27

Note. VS = Very soft; S = Soft; C= Comfortable; L = Loud; TL = Too loud; * = $p < 0.05$; *** = $p < 0.001$; BF_{10} = Bayes factor favouring the alternate hypothesis.

Table 4.23

Significance of difference in intensity required to identify loudness levels of vowels, measured using Kruskal-Wallis test, across the three participant groups (typically developing children, children using cochlear implants, & children using the 'test hearing aids' in non-linear setting)

Loudness level	**Stimuli**											
	/u/				**/a/**				**/i/**			
	df	**χ^2**	***p***	**BF_{10}**	***df***	**χ^2**	***p***	**BF_{10}**	***df***	**χ^2**	***p***	**BF_{10}**
VS	2	20.88	< 0.001***	16213.21	2	22.48	< 0.001***	48162.81	2	20.75	< 0.001***	28316.07
S	2	5.93	0.05	1.22	2	5.40	0.07	1.17	2	2.08	0.35	0.54
C	2	4.60	0.1	1.73	2	6.14	0.05	2.22	2	1.80	0.41	0.45
L	2	0.86	0.65	0.24	2	3.57	0.17	0.46	2	4.37	0.11	1.03
TL	2	2.61	0.27	0.76	2	0.20	0.90	0.40	2	0.07	0.97	0.35

Note. VS = Very soft; S = Soft; C= Comfortable; L = Loud; TL = Too loud; * = $p < 0.05$; *** = $p < 0.001$; BF_{10} = Bayes factor favouring the alternate hypothesis

Table 4.24

Comparison of intensity (dB HL) required to identify loudness levels by typically developing children (TDC) with children using the 'test hearing aids' in non-linear setting (HA-NL), measured using Mann-Whitney U test

Stimuli	***Loudness level***	***Groups***	***Median (Q1 – Q3)***	***Mann-Whitney U results***			***BF_{10}***
				U	***p***	***r***	
500 Hz	VS	TDC	25 (20 - 25)	71.50	0.02	-0.35	1.58
		HA-NL	32.5 (26.25 - 43.75)				
	C	TDC	65 (62.5 - 67.5)	62.50	0.001*	-0.52	45.99
		HA-NL	70 (67.5 - 74.38)				
	L	TDC	80 (77.5 - 87.5)	36.50	0.001*	-0.53	53.65
		HA-NL	92.5 (87.5 - 95)				
1000 Hz	VS	TDC	22.5 (17.5 - 25.62)	1.00	< 0.001***	-0.70	6.163×10^6
		HA-NL	41.25 (31.88 - 48.75)				
	S	TDC	47.5 (41.875 - 52.5)	64.00	0.001*	-0.50	57.00
		HA-NL	55 (48.13 - 66.25)				
	C	TDC	67.5 (65 - 70)	80.00	0.004*	-0.44	42.62
		HA-NL	75 (72.5 - 89.37)				
4000 Hz	VS	TDC	25 (22.5 - 27.5)	3.00	< 0.001***	-0.65	198375.35
		HA-NL	42.5 (37.5 - 55)				
	S	TDC	52.5 (47.5 - 55)	115.50	0.11	-0.24	0.42
		HA-NL	55 (50 - 65)				
/u/	VS	TDC	25 (20 - 27.5)	24.50	0.002*	-0.52	78.30
		HA-NL	32.5 (27.5 - 37.5)				
/a/	VS	TDC	20 (20 - 25)	20.50	0.001*	-0.54	194.18
		HA-NL	32.5				

			(25- 37.5)				
/i/	VS	TDC	22.5 (17.5 - 25)	36.50	0.003*	-0.49	108.85
		HA-NL	31.25 (25 - 39.38)				

Note. * = $p < 0.0167$; *** = $p < 0.001$; r (effect size) = $z/\sqrt{n}$; BF_{10} = Bayes factor favouring the alternate hypothesis; VS = Very soft; S = Soft; C = Comfortable; L = Loud; TL = Too loud.

The Mann-Whitney U test indicated that a significant difference was present between the typically developing children and the children using the non-linear ‘test hearing aids’ (Table 4.24) for most of the stimuli at low loudness levels. At 500 Hz warble, such a difference was observed only at louder levels. For most of the stimuli / loudness levels that had significant differences, the Bayes factor values were high indicating that the significant difference was valid.

The significant difference seen on the Mann-Whitney U test between children using cochlear implants and those wearing non-linear ‘test hearing aids’ was more for stimuli at the softer loudness levels (Table 4.25). This was majorly seen only for warble-tones at 1000 Hz and 4000 Hz.

Table 4.25

Comparison of intensity (dB HL) required to identify loudness levels by children using cochlear implants (CI) and children using the ‘test hearing aids’ in non-linear setting (HA-NL), measured using Mann-Whitney U test

Stimuli	***Loudness level***	***Groups***	***Median (Q1 – Q3)***	***Mann-Whitney U results***			***BF_{10}***
				U	***p***	***r***	
500 Hz	VS	CI	35 (28.75 - 40.63)	39.00	0.62	-0.11	0.31
		HA-NL	32.5 (26.25 - 43.75)				
	Cable	CI	68.75 (63.13 - 77.5)	65.50	0.70	-0.08	0.29
		HA-NL	70				

			(67.5 - 74.38)				
	L	CI	85 (80 - 88.75)	14.00	0.03	-0.52	1.05
		HA-NL	92.5 (87.5 - 95)				
1000 Hz	VS	CI	33.75 (29.38 - 37.5)	18.00	0.05	-0.47	1.63
		HA-NL	41.25 (31.88 - 48.75)				
	S	CI	45 (42.5 - 51.88)	22.50	0.004*	-0.59	8.01
		HA-NL	55 (48.13 - 66.25)				
	C	CI	68.75 (65 - 75)	38.50	0.05	-0.40	1.52
		HA-NL	75 (72.5 - 89.37)				
4000 Hz	VS	CI	35 (30 - 37.5)	7.50	0.006*	-0.66	8.16
		HA-NL	42.5 (37.5 - 55)				
	S	CI	45 (42.5 - 47.5)	20.00	0.004*	-0.59	3.18
		HA-NL	55 (50 - 65)				
/u/	VS	CI	35 (30 - 40)	22.50	0.52	-0.17	0.30
		HA-NL	32.5 (27.5 - 37.5)				
/a/	VS	CI	31.25 (30 - 36.88)	26.00	0.81	-0.06	0.27
		HA-NL	32.5 (25 - 37.5)				
/i/	VS	CI	33.75 (28.13 - 36.88)	26.50	0.56	-0.15	0.30
		HA-NL	31.25 (25 - 39.38)				

Note. * = $p < 0.0167$; *** = $p < 0.001$; r (effect size) = $z/\sqrt{n}$; BF_{10} = Bayes factor favouring the alternate hypothesis; VS = Very soft; S = Soft; C = Comfortable; L = Loud; TL = Too loud.

Further, *canonical discriminant analysis* was measured to determine which variables differentiated the three groups. Two functions were obtained with eigen values of 1.51 and 1.14. The percentage of variance explained by these functions were 56.9% and 43.1% respectively. Further, a significant Wilk's lambda for functions 1 and 2 ($\lambda = .19$; $p < 0.001$) as well as function 2 ($\lambda = .47$; $p = 0.009$) indicated significant difference in the mean scores of the three groups. Table 4.26 provides the structure coefficients for the predictor variables. The discriminant function accurately classified 83.9% of the typically developing children, 91.7% of the children using cochlear implants and 100% of the children using the ‘test hearing aids’ with non-linear setting correctly. The overall classification accuracy was 89.3%. Three of the typically developing children were misclassified as children using cochlear implants and two of them were misclassified as children using hearing aids. Only one child using cochlear implant was misclassified as a typically developing child. However, none of the children using hearing aids were misclassified.

Figure 4.10 depicted the canonical scores plot for the loudness growth identification for the three groups for the two discriminant functions. From the figure it can be observed that Function 1 differentiated children using hearing aids from the other two groups. Table 4.26 indicates that the groups were mainly differentiated by three predictor variables. These included ‘1000 Hz, soft’, followed by ‘500 Hz, loud’, and ‘/a/, comfortable’. Function 2 differentiated all three groups, but to a lesser extent (Figure 4.10). The four predictor variables that differentiated the three groups included ‘4000 Hz, soft’, ‘/a/, comfortable’, ‘4000 Hz, loud’, and ‘/u/, soft’ (Table 4.26). Further, from Table 4.26 it can be seen that the variables in Function 1 had relatively higher weightage compared to the variables in Function 2.

Table 4.26

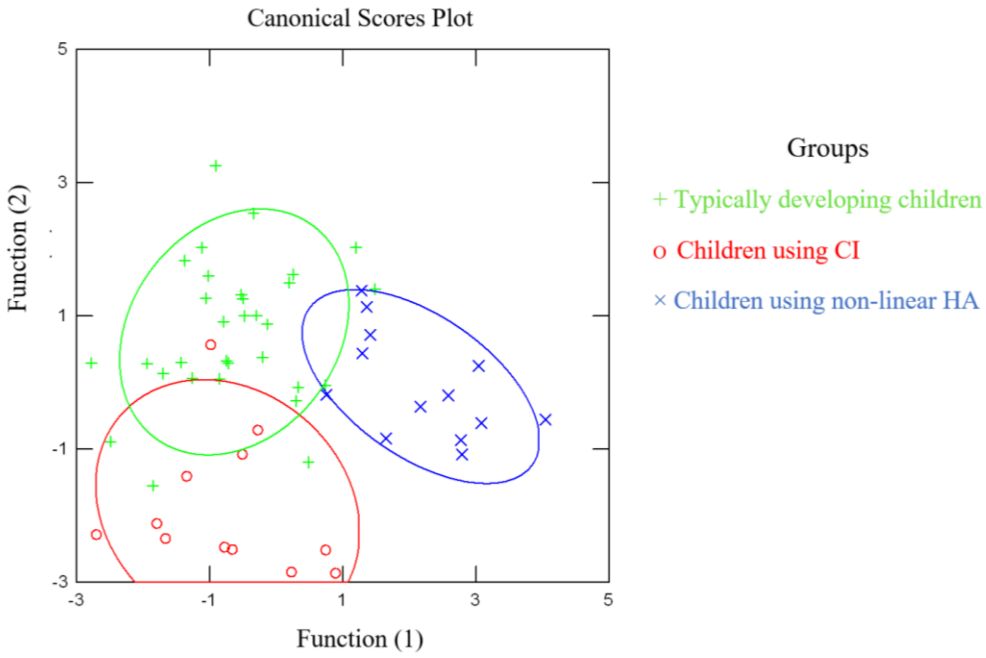
Standardised discriminant function, structure canonical coefficients and effect size for each predictor variable for discriminating the typically developing children, children using cochlear implants and children using the 'test hearing aids' in non-linear setting.

Variables		**Function 1**			**Function 2**		
		Standardised discriminant function coefficients	**Structure canonical coefficients *(r)***	**Effect size *(r^2)***	**Standardised discriminant function coefficients**	**Structure canonical coefficients *(r)***	**Effect size *(r^2)***
500 Hz	S	.07	0.27	0.07	-.24	0.14	0.02
	C	-.37	0.37	0.14	.53	0.31	0.10
	L	.90	0.52	0.27	.42	0.23	0.05
1000 Hz	S	.99	0.55	0.30	.52	0.02	0.00
	C	-.07	0.51	0.26	-.54	0.06	0.00
	L	-.33	0.26	0.07	.28	0.08	0.01
4000 Hz	S	-.15	0.26	0.07	-.95	-0.28	0.08
	C	-.19	0.04	0.00	.45	-0.07	0.00
	L	.35	0.30	0.09	-.73	-0.19	0.04
/u/	S	-.28	0.29	0.08	.68	0.16	0.03
	C	.51	0.27	0.07	.06	0.23	0.05
	L	-.50	0.06	0.00	.00	0.10	0.01
/a/	S	-.19	0.34	0.12	-.23	-0.07	0.00
	C	.66	0.33	0.11	-.77	-0.09	0.01
	L	.06	0.23	0.05	.02	-0.13	0.02
/i/	S	.16	0.15	0.02	.48	0.16	0.03
	C	-.53	0.10	0.01	-.15	0.20	0.04
	L	.09	0.13	0.02	.49	0.30	0.09

Note. S = Soft; C = Comfortable; L = Loud.

Figure 4.10

Canonical scores plotted across the two discriminant functions for loudness identification in typically developing children, children using cochlear implants (CI) and children using the 'test hearing aids' in non-linear settings (HA). The ellipses show 95% confidence boundaries of each group.



The overall results comparing the intensity required to identify loudness levels by the three groups of participants [typically developing children, children using cochlear implants, and children using hearing aids in three conditions (own prescribed hearing aids, 'test hearing aids' with linear as well as non-linear settings)] indicated that there was a significant difference between them. This was seen mainly for the low loudness levels. The typically developing children required lesser intensity to perceive low loudness levels compared to the children using cochlear implants for all stimuli. Similarly, the typically developing children required lesser intensity to perceive low loudness levels compared to the children using hearing aids, in all the three conditions, for all stimuli. However, for the 500 Hz warble-tone, the typically developing children required lesser intensity compared to the children using hearing aids in linear settings across all five loudness levels. Likewise, the children using cochlear implants needed lower intensities compared to the children using their own-prescribed hearing aids for the perception of low loudness levels (‘very soft’ & ‘soft’) of the high-frequency warble-tone (4000 Hz). Similar findings were obtained when the loudness growth identification of children using cochlear implants were compared with that of children using non-linear hearing aids. However, the children using cochlear implants and the children using hearing aids did not have significant differences in loudness growth perception of vowels.

4.4 Comparison of Intensity Discrimination Between Participant Groups (Typically Developing Children, Children using Cochlear Implants, & Children using Hearing Aids)

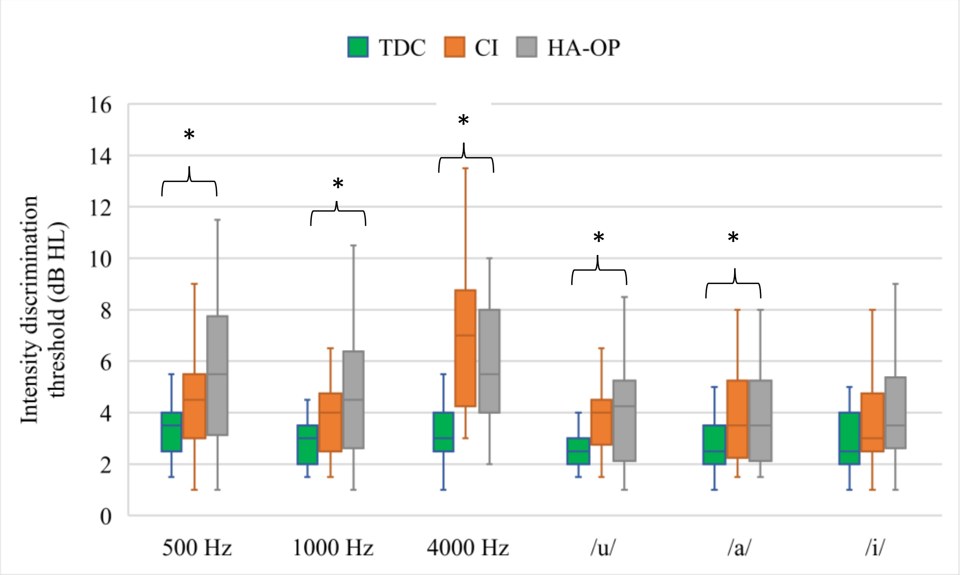
Intensity discrimination was compared between the three groups (typically developing children, children using cochlear implants, & children using hearing aids) in three conditions. The three conditions differed in terms of the hearing aids worn by the third group. In the first condition the comparison was done with them wearing their own prescribed hearing aids and in the other two conditions them wearing ‘test hearing aids’ with linear setting, and ‘test hearing aids’ with non-linear setting.

4.4.1 Comparison of Intensity Discrimination between the Typically Developing Children, Children using Cochlear Implants, and Children using their Own Prescribed Hearing Aids.

The median, 25th and 75th percentile of the intensity discrimination thresholds, depicted in Figure 4.11 indicate that the typically developing children always obtained lower thresholds in comparison to the other two groups. Further, the intensity discrimination threshold got by the children using cochlear implants were lower compared to that got by children using hearing aids for most of the stimuli. However, the differences between the two clinical groups were comparable.

Figure 4.11

Median, 25th - 75th percentile, and significance of difference of intensity discrimination thresholds for typically developing children (TDC), children using cochlear implants (CI) and children using their own prescribed hearing aids (HA-OP)



Note. * = $p < 0.05$, measured using Kruskal-Wallis test

To establish if the three groups differed statistically, Kruskal-Wallis test was conducted separately for each stimulus (Table 4.27). A statistically significant difference was present for all the stimuli except vowel /i/. For the stimuli that had a significant different, Mann-Whitney U test was conducted to determine which of the pairs of groups differed from each other.

Table 4.27

Significance of difference of intensity discrimination thresholds between the three participant groups (typically developing children, children using cochlear implants & children using own prescribed hearing aids) measured using Kruskal-Wallis test

Loudness level	**Stimuli**					
	500 Hz	**1000 Hz**	**4000 Hz**	**/u/**	**/a/**	**/i/**
Df	2	2	2	2	2	2
χ^2	9.44	7.91	28.38	15.18	8.43	4.33
p	0.009**	0.02*	< 0.001***	0.001**	0.015*	0.11
BF_{10}	14.42	9.51	14217.76	141.09	6.35	1.32

Note. * = $p < 0.05$; ** = $p < 0.01$; *** = $p < 0.001$; BF_{10} = Bayes factor favouring the alternate hypothesis

Mann-Whitney U tests indicated that for most parameters the typically developing had significantly lower discrimination thresholds when compared to the two groups using hearing devices (Table 4.28). On the other hand, between the two clinical groups (children using cochlear implants & children using their own prescribed hearing aids), no statistically significant difference was noted for any of the stimuli.

Table 4.28

Significance of difference in intensity discrimination thresholds between pairs of the participant groups [typically developing children (TDC), children using cochlear implants (CI) and children using their own prescribed hearing aids (HA-OP)] evaluated using Mann-Whitney U test

Stimuli	***Groups***	***Median (Q1 – Q3)***	***Mann-Whitney U results***				***BF₁₀***
			n	***U***	***p***	***r***	
500 Hz	TDC	3.5 (2.50 - 4)	56	237	0.012*	-0.33	3.64
	CI	4.50 (3 - 5.50)					
1000 Hz	TDC	3	56	253	0.03	-0.30	3.35

		(2 - 3.50)					
	CI	4 (2.50 - 4.75)					
4000 Hz	TDC	3 (2.50 - 4)	56	94.5	< 0.001***	-0.65	5004.67
	CI	7 (4.25 - 8.75)					
/u/	TDC	2.50 (2 - 3)	56	170.5	< 0.001***	-0.48	176.76
	CI	4 (2.75 - 4.50)					
/a/	TDC	2.50 (2 - 3.50)	56	231	0.009*	-0.35	6.25
	CI	3.50 (2.25 - 5.25)					
500 Hz	TDC	3.5 (2.50 - 4)	51	177.5	0.010*	-0.36	14.87
	HA-OP	5.50 (3.13 - 7.75)					
1000 Hz	TDC	3 (2 - 3.50)	51	186.5	0.016*	-0.34	14.08
	HA-OP	4.50 (2.63 - 6.38)					
4000 Hz	TDC	3 (2.50 - 4)	51	107.5	< 0.001***	-0.55	1627.03
	HA-OP	5.50 (4.00 - 8.00)					
/u/	TDC	2.50 (2 - 3)	51	162	0.004*	-0.41	74.42
	HA-OP	4.25 (2.13 - 5.25)					
/a/	TDC	2.50 (2 - 3.50)	51	194	0.02	-0.32	5.33
	HA-OP	3.50 (2.13 - 5.25)					
500 Hz	CI	4.50 (3 - 5.50)	49	211	0.37	-0.13	0.3
	HA-OP	5.50 (3.13 - 7.75)					
1000 Hz	CI	4 (2.50 - 4.75)	49	213.5	0.4	-0.12	0.27
	HA-OP	4.50 (2.63 - 6.38)					
4000 Hz	CI	7 (4.25 - 8.75)	49	206	0.31	-0.14	0.38
	HA-OP	5.50 (4.00 - 8.00)					
/u/	CI	4	49	232	0.68	-0.06	0.18

		(2.75 - 4.50)					
	HA-OP	4.25 (2.13 - 5.25)					
/a/	CI	3.50 (2.25 - 5.25)	49	249	0.98	0	0.17
	HA-OP	3.50 (2.13 - 5.25)					

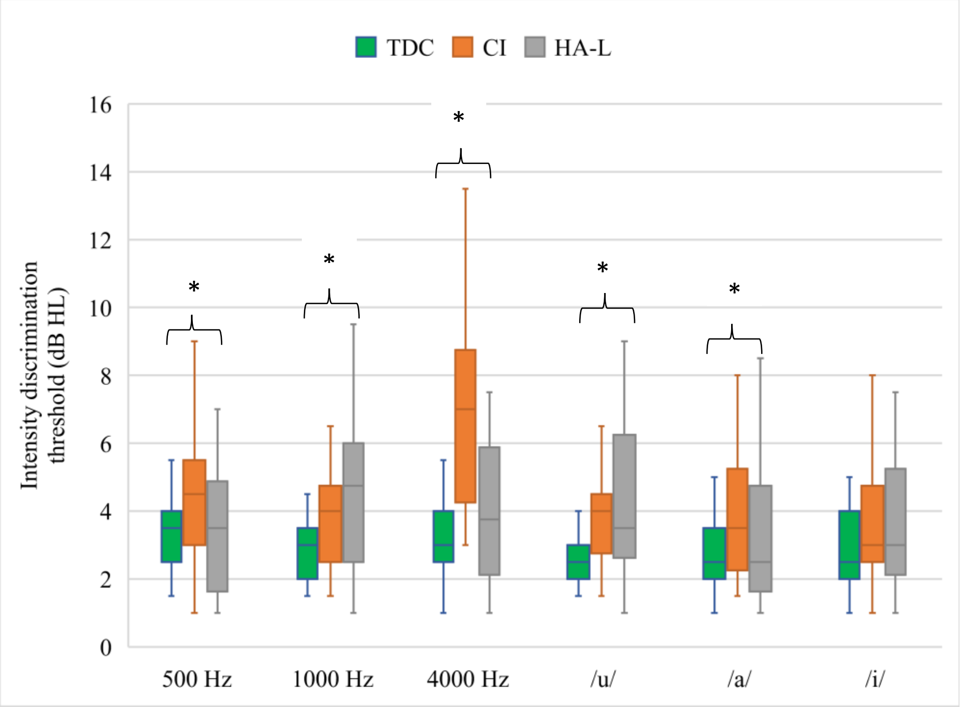
Note. * = $p < 0.0167$; *** = $p < 0.001$; r (effect size) = $z/\sqrt{n}$; BF_{10} = Bayes factor favouring the alternate hypothesis

4.4.2 Comparison of Intensity Discrimination between the Typically Developing Children, Children using Cochlear Implants, and Children using 'Test Hearing Aids' in Linear Setting

The median, 25th and 75th percentile of the intensity discrimination thresholds between the three groups of children, (typically developing children, children using cochlear implants, & children using the 'test hearing aids' in linear setting), varied depending on the stimulus (Figure 4.12). The intensity discrimination thresholds were minimum for the typically developing children for the six stimuli, with it being comparable for most stimuli for the other two groups. Further, Kruskal-Wallis test was done to confirm if the differences between groups were statistically different. A significant difference was noted for all the stimuli except the vowel /i/ (Table 4.29). Thus, Mann-Whitney U test was conducted for the stimuli that had a significant difference (Table 4.30). As the comparison between the typically developing children and the children using cochlear implants was done in the earlier section (4.4.1), it has not been given again.

Figure 4.12

Median, 25th - 75th percentile and significance of difference of the intensity discrimination thresholds for typically developing children (TDC), children using cochlear implants (CI) and children using the 'test hearing aids' with linear settings (HA-L)



Note. * = $p < 0.05$, measured using Kruskal-Wallis test

Table 4.29

Significance of difference in intensity discrimination thresholds, measured using Kruskal-Wallis test across the three participant groups (typically developing children, children using cochlear implants, & children using the 'test hearing aids' in linear setting)

	Stimuli					
	500 Hz	**1000 Hz**	**4000 Hz**	**/u/**	**/a/**	**/i/**
Df	2	2	2	2	2	2
χ^2	6.66	8.31	24.02	15.42	6.37	2.23
p	0.04*	0.02*	< 0.001***	< 0.001***	0.04*	0.33
BF_{10}	2.27	10.63	20113.13	101.53	1.63	0.59

Note. * = $p < 0.05$; *** = $p < 0.001$; BF_{10} = Bayes factor favouring the alternate hypothesis

Table 4.30

Significance of difference in intensity discrimination thresholds between pairs of the participant groups [children using the 'test hearing aids' in linear setting (HA-L) with typically developing children (TDC) & children using cochlear implants (CI)] evaluated using Mann-Whitney U test

Stimuli	*Groups*	*Median (Q1 – Q3)*	*Mann-Whitney U results*				BF_{10}
			n	*U*	*p*	*r*	
500 Hz	TDC	3.50 (2.50 - 4)	51	293.00	0.74	-0.05	0.17
	HA-L	3.50 (1.63 - 4.88)					
1000 Hz	TDC	3.00 (2 - 3.50)	51	182.50	0.013*	-0.35	25.57
	HA-L	4.75 (2.5 - 6)					
4000 Hz	TDC	3.00 (2.50 - 4)	51	250.00	0.25	-0.16	0.46
	HA-L	3.75 (2.13 - 5.88)					
/u/	TDC	2.50 (2 - 3)	51	158.50	0.003*	-0.41	51.76
	HA-L	3.5 (2.62 - 6.25)					
/a/	TDC	2.50 (2 - 3.50)	51	283.50	0.61	-0.07	0.53
	HA-L	2.5 (1.63 - 4.75)					
500 Hz	CI	3.50 (2 - 4)	45	168.50	0.06	-0.28	0.71
	HA-L	3.50 (1.63 - 4.88)					
1000 Hz	CI	4.50 (3 - 5.50)	45	207.50	0.33	-0.15	0.23
	HA-L	4.75 (2.5 - 6)					
4000 Hz	CI	4.00 (2.50 - 4.75)	45	114.50	0.002*	-0.46	10.84
	HA-L	3.75 (2.13 - 5.88)					
/u/	CI	7.00 (4.25 - 8.75)	45	241.00	0.84	-0.03	0.22

	HA-L	3.5 (2.62 - 6.25)					
/a/	CI	4.00 (2.75 - 4.50)	45	188.00	0.15	-0.21	0.20
	HA-L	2.5 (1.63 - 4.75)					

Note. * = level of significance with $p < 0.0167$; r (effect size) = $z/\sqrt{n}$; BF_{10} = Bayes factor favouring the alternate hypothesis

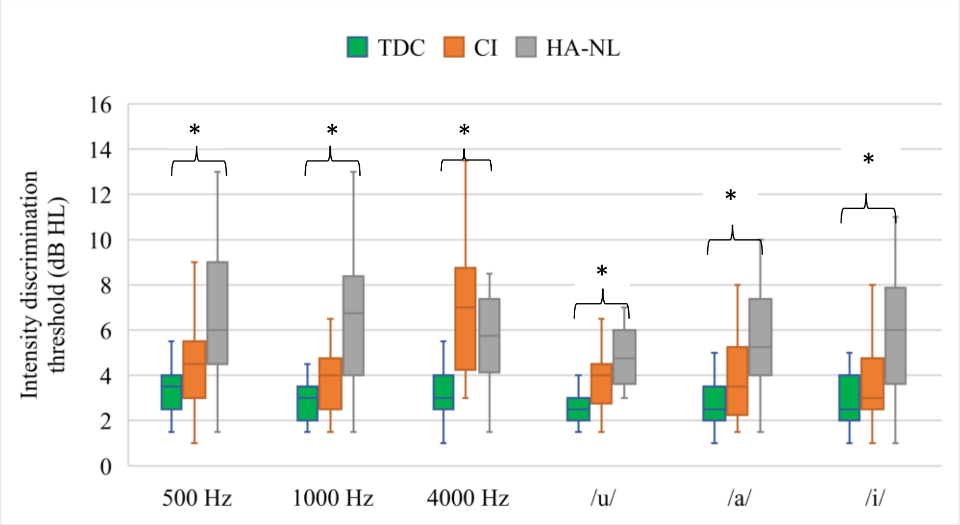
Mann-Whitney U test results indicated that there was a significant difference between intensity discrimination thresholds of the typically developing children and children using hearing aids in the linear setting for only a limited number of stimuli (1000 Hz warble-tone & vowel /u/). Similarly, such a statistically significant difference between the children using cochlear implants and children using hearing aids in linear settings was noted only for the 4000 Hz warble-tone (Table 4.30).

4.4.3 Comparison of Intensity Discrimination between the Typically Developing Children, Children using Cochlear Implants, and Children using 'Test Hearing Aids' in Non-Linear Settings

The intensity discrimination thresholds (median & 25th - 75th percentile) varied markedly in the group wearing the 'test hearing aids' in a non-linear setting, compared to the other two groups of participants (Figure 4.13). The thresholds were the poorest for the children using the non-linear 'test hearing aids' for all the stimuli except 4000 Hz. At 4000 Hz, the children using cochlear implants obtained higher thresholds. Kruskal-Wallis test was conducted to confirm the presence of a statistical difference for each stimulus (Table 4.31). Significant differences were observed across the typically developing children, the children using hearing aids in a non-linear setting, and the children using cochlear implants. This was observed for all six stimuli.

Figure 4.13

Median, 25th - 75th percentile, and significance of difference of intensity discrimination thresholds for typically developing children (TDC), children using cochlear implants (CI) and children using hearing aids with non-linear settings (HA-NL)



Note. * = $p < 0.05$, measured using Kruskal-Wallis test

Table 4.31

Significance of difference in intensity discrimination thresholds, measured using Kruskal-Wallis test across the three participant groups (typically developing children, children using cochlear implants, & children using 'test hearing aids' in non-linear setting)

	Stimuli					
	500 Hz	**1000 Hz**	**4000 Hz**	**/u/**	**/a/**	**/i/**
Df	2	2	2	2	2	2
χ^2	17.83	22.56	28.19	32.67	18.98	17.27
p	< 0.001***	< 0.001***	< 0.001***	< 0.001***	< 0.001***	< 0.001***
BF_{10}	3737.04	115514.97	17681.016	84449.84	1943.36	4072.53

Note. *** = $p < 0.001$; BF_{10} = Bayes factor favouring the alternate hypothesis

Table 4.32

Significance of difference in intensity discrimination thresholds between pairs of the participant groups [children using hearing aids in non-linear setting (HA-NL) with typically developing children (TDC) & children using cochlear implants (CI)], evaluated using Mann-Whitney U test

Stimuli	**Groups**	**Median (Q1 – Q3)**	***Mann-Whitney U results***				***BF*$_{10}$**
			n	***U***	***p***	***r***	
500 Hz	TDC	3.50 (2.50 - 4)	51	110.00	< 0.001***	-0.54	1955.65
	HA-NL	6.00 (4.5 - 9)					
1000 Hz	TDC	3.00 (2 - 3.50)	51	75.50	< 0.001***	-0.64	96423.42
	HA-NL	6.75 (4 - 8.38)					
4000 Hz	TDC	3.00 (2.50 - 4)	51	109.50	< 0.001***	-0.54	1095.10
	HA-NL	5.75 (4.13 - 7.38)					
/u/	TDC	2.50 (2 - 3)	51	29.50	< 0.001***	-0.77	43173.77
	HA-NL	4.75 (3.63 - 6)					
/a/	TDC	2.50 (2 - 3.50)	51	98.50	< 0.001***	-0.57	6833.35
	HA-NL	5.25 (4 - 7.38)					
/i/	TDC	3.50 (2 - 4)	51	98.50	< 0.001***	-0.58	9998.56
	HA-NL	6 (3.63 - 7.88)					
500 Hz	CI	4.50 (3 - 5.50)	45	148.00	0.02	-0.35	3.16
	HA-NL	6 (4.5 - 9)					
1000 Hz	CI	4.00 (2.50 - 4.75)	45	124.00	0.004*	-0.43	11.62
	HA-NL	6.75 (4 - 8.38)					
4000 Hz	CI	7.00 (4.25 - 8.75)	45	201.50	0.27	-0.17	0.55
	HA-NL	5.75					

		(4.13 - 7.38)					
/u/	CI	4.00 (2.75 - 4.50)	45	153.50	0.03	-0.33	2.15
	HA-NL	4.75 (3.63 - 6)					
/a/	CI	3.50 (2.25 - 5.25)	45	157.50	0.03	-0.32	1.05
	HA-NL	5.25 (4 - 7.38)					
/i/	CI	3.00 (2.50 - 4.75)	45	130.50	0.006*	-0.41	5.19
	HA-NL	6 (3.63 - 7.88)					

Note. * = $p < 0.0167$; *** = $p < 0.001$; r (effect size) = $z/\sqrt{n}$; BF_{10} = Bayes factor favouring the alternate hypothesis

Mann-Whitney U test was conducted to compare pairs of groups. Between the typically developing children and children using cochlear implants, significant differences were obtained for the 4000 Hz warble-tone and vowels /u/ and /a/. Similarly, the children using cochlear implants and the children using the ‘test hearing aids’ in a non-linear setting differed significantly only for the 1000 Hz warble-tone and vowel /i/ (Table 4.32). However, between the typically developing children and children using the ‘test hearing aids’ in a non-linear setting, there were significant differences for all six stimuli.

The test-retest reliability of the intensity discrimination thresholds, measured on ~10% of the participants, was measured using Cronbach’s alpha. The high Cronbach’s alpha value of 0.89 indicated that the responses obtained from the three participant groups was reliable.

Thus, the comparison of the intensity discrimination thresholds between the three groups indicated that the typically developing children had significantly better thresholds than the children using cochlear implants, and the children using hearing aids. This was seen for most of the stimuli. An exception to this was the condition where the children using the ‘test hearing aids’ in linear setting. In this condition they had almost similar thresholds as the typically developing children. Additionally, the children using cochlear implants also had almost similar intensity discrimination as children using hearing aids.

From the overall findings of the results on loudness growth identification (summarised in Table 4.33 and Table 4.34) the following were obtained:

- Among the children using hearing aids, there was no significant difference in loudness growth identification between the three hearing aid conditions, except between linear and non-linear settings at louder levels of 1000 Hz.
- The children using cochlear implants had significantly poorer loudness growth identification than the typically developing children, majorly at low intensities.
- The children using hearing aids also had significantly poorer loudness growth identification than the typically developing children, majorly at low intensities.
- The children using cochlear implants had significantly better loudness growth identification than the children using their own-prescribed hearing aids at low intensities for the high frequency warble-tone.
- The children using cochlear implants had significantly better loudness growth identification than the children using hearing aids with non-linear settings at low intensities for the high-frequency warble-tone.
- However, when vowels were utilized, no significant difference was noted between the children using cochlear implants and the children using hearing aids in all the three conditions.

Further, it can be inferred from the results on intensity discrimination (Table 4.35 & Table 4.36) that:

- The intensity discrimination thresholds were significantly better when hearing aid users used linear hearing aids than their own-prescribed hearing aids for 500 Hz and 4000 Hz.
- The discrimination thresholds were significantly better when the children used linear hearing aids compared to the non-linear hearing aids for 500 Hz, 1000 Hz, 4000 Hz, and /i/.
- No significant difference was obtained between the thresholds of the children using their own-prescribed hearing aids and them ‘test hearing aids’ with non-linear settings.
- The children using cochlear implants obtained significantly poorer discrimination thresholds than the typically developing children for the 500 Hz and 4000 Hz warble-tones and the low and mid-frequency vowels, /u/ and /a/, respectively.
- The discrimination thresholds of children using their own-prescribed hearing aids were significantly poorer than typically developing children for all the warble-tones. However, the thresholds were significantly poorer only for the low-frequency vowel /u/.
- The intensity discrimination thresholds for children using linear hearing aids were significantly poorer than that of the typically developing children for the 1000 Hz warble-tone and the low-frequency vowel /u/.
- The children using non-linear hearing aids obtained significantly poorer thresholds than the typically developing children for all three warble-tones as well as all three vowels.

- There was no significant difference observed between children using cochlear implants and the children using own-prescribed hearing aids.
- The intensity discrimination thresholds of children using linear hearing aids were significantly poorer than the children using cochlear implants at 4000 Hz. However, no statistically significant difference was noted for vowels.
- The intensity discrimination thresholds of children using non-linear hearing aids were significantly poorer than the children using cochlear implants for the 1000 Hz warble-tone and the high-frequency vowel /i/.

Table 4.33

Summary of the significance of difference of intensity required to perceive loudness levels of warble-tones in the three participant groups [typically developing children (TDC), children using cochlear implants (CI), & children using hearing aids that included own prescribed hearing aids (HA-OP), 'test hearing aids' in linear setting (HA-L) & 'test hearing aids' in non-linear setting (HA-NL)]

Groups		**CI**					**HA-OP**					**HA-L**					**HA-NL**				
	Stimuli	**VS**	**S**	**C**	**L**	**TL**	**VS**	**S**	**C**	**L**	**TL**	**VS**	**S**	**C**	**L**	**TL**	**VS**	**S**	**C**	**L**	**TL**
TDC	500 Hz	**	NS	NS	NS	NS	**	*	NS	NS	*	*	**	*	*	*	NS	NS	*	*	NS
	1000 Hz	**	NS	NS	NS	NS	**	NS	NS	NS	NS	**	NS	NS	NS	NS	**	**	*	NS	NS
	4000 Hz	**	*	NS	NS	NS	**	*	NS	NS	NS	**	NS	NS	NS	NS	**	NS	NS	NS	NS
CI	500 Hz						NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
	1000 Hz						NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	*	NS	NS	NS
	4000 Hz						*	*	NS	NS	NS	NS	NS	NS	NS	NS	*	*	NS	NS	NS
HA-OP	500 Hz											NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
	1000 Hz											NS	NS	NS	NS	NS	NS	NS	*	NS	NS
	4000 Hz											NS	*	NS	NS	NS	NS	NS	NS	NS	NS
HA-L	500 Hz																NS	NS	NS	NS	NS
	1000 Hz																NS	NS	*	*	NS
	4000 Hz																NS	NS	NS	NS	NS

Note. VS = Very soft; S = Soft; C = Comfortable; L = Loud; TL = Too loud; * = $p < 0.0167$; ** = $p < 0.001$; NS = Not significant

Table 4.34

Summary of the significance of difference of intensity required to perceive loudness levels of vowels in the three participant groups [typically developing children (TDC), children using cochlear implants (CI), & children using hearing aids that included own prescribed hearing aids (HA-OP), 'test hearing aids' in linear setting (HA-L) & 'test hearing aids' in non-linear setting (HA-NL)]

Groups ↳		**CI**					**HA-OP**					**HA-L**					**HA-NL**				
	Stimuli	**VS**	**S**	**C**	**L**	**TL**	**VS**	**S**	**C**	**L**	**TL**	**VS**	**S**	**C**	**L**	**TL**	**VS**	**S**	**C**	**L**	**TL**
TDC	/u/	**	NS	NS	NS	NS	**	NS	NS	NS	NS	**	*	NS	NS	NS	**	NS	NS	NS	NS
	/a/	**	NS	NS	NS	NS	**	NS	NS	NS	NS	**	NS	NS	NS	NS	**	NS	NS	NS	NS
	/i/	**	NS	NS	NS	NS	**	*	NS	NS	NS	**	NS	NS	NS	NS	**	*	NS	NS	NS
CI	/u/						NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
	/a/						NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
	/i/						NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
HA-OP	/u/											NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
	/a/											NS	NS	NS	NS	NS	NS	NS	*	*	NS
	/i/											NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
HA-L	/u/																NS	NS	NS	NS	NS
	/a/																NS	NS	*	NS	NS
	/i/																NS	NS	NS	NS	NS

Note. VS = Very soft; S = Soft; C = Comfortable; L = Loud; TL = Too loud; * = $p < 0.0167$; ** = $p < 0.001$; NS = Not significant

Table 4.35

Summary of factors that differentiated the three participant groups (typically developing children, children using cochlear implants & children using hearing aids in three conditions) using discriminant function analysis.

Groups compared	Function Number	#Groups Differentiated	†Stimuli perceived differently by pairs of groups (in order of higher to lower loading)	Remarks
TDC Vs CI Vs HA-OP	1	TDC Vs HA-OP	/i/, Loud; 500 Hz, Comfortable; 4000 Hz, Soft; /i/, Comfortable; /i/, Soft	Children using CI were differentiated to a lesser extent from the 2 other groups, for both F1 & F2.
	2	TDC Vs HA-OP	4000 Hz, Soft; 500 Hz, Soft; 500 Hz, Comfortable; 1000 Hz, Loud	
TDC Vs CI Vs HA-L	1	TDC Vs HA-L	500 Hz, loud; /i/, Comfortable; 1000 Hz, Comfortable; /i/, Soft; /a/, Comfortable	Children using CI were discriminated to a lesser extent from the 2 other groups, for both F1 & F2.
	2	Could not differentiate any of the three groups discretely		
TDC Vs CI Vs HA-NL	1	TDC Vs HA-NL; CI Vs HA-NL	1000 Hz, Soft; 500 Hz, Loud; /a/, Comfortable	-
	2	TDC Vs CI; CI Vs HA-NL	4000 Hz, Soft; /a/, Comfortable; 4000 Hz, Loud; /u/, Soft	-

Note. #Based on percentage of children in each group that was differentiated and canonical score plots (Figures 4.6, 4.8, & 4.10) of the discriminant analysis; †Based on standardised discriminant function (Tables 4.16, 4.21, & 4.26); TDC = typically developing children; CI = children using cochlear implants; HA-OP = children using own prescribed hearing aids; HA-L = children using linear hearing aids; HA-NL = children using non-linear hearing aids

Table 4.36

Summary of the significance of difference of intensity discrimination thresholds for warble-tones in the three participant groups [typically developing children (TDC), children using cochlear implants (CI), & children using hearing aids that included own prescribed hearing aids (HA-OP), 'test hearing aids' in linear setting (HA-L), & 'test hearing aids' in non-linear setting (HA-NL)]

Stimuli	**Groups**	**CI**	**HA-OP**	**HA-L**	**HA-NL**
500 Hz	**TDC**	*	*	NS	**
1000 Hz		NS	*	*	**
4000 Hz		**	**	NS	**
500 Hz	**CI**		NS	NS	NS
1000 Hz			NS	NS	*
4000 Hz			NS	*	NS
500 Hz	**HA-OP**			*	NS
1000 Hz				NS	NS
4000 Hz				**	NS
500 Hz	**HA-L**				**
1000 Hz					*
4000 Hz					*

Note. * = $p < 0.0167$; ** = $p < 0.001$; NS = Not significant

Table 4.37

Summary of the significance of difference of intensity discrimination thresholds for vowels in the three participant groups (typically developing children [TDC], children using cochlear implants [CI], children using own prescribed hearing aids [HA-OP], children using 'test hearing aids' in linear setting [HA-L] & children using 'test hearing aids' in non-linear setting [HA-NL]

Stimuli	**Groups**	**CI**	**HA_OP**	**HA_L**	**HA_NL**
/u/	**TDC**	**	*	*	**
/a/		*	NS	NS	**
/i/		NS	NS	NS	**
/u/	**CI**		NS	NS	NS
/a/			NS	NS	NS
/i/			NS	NS	*
/u/	**HA-OP**			NS	NS
/a/				NS	NS
/i/				NS	NS
/u/	**HA-L**				NS
/a/					NS
/i/					**

Note. * = $p < 0.0167$; ** = $p < 0.001$; NS = Not significant

5. Discussion

The results of the current research that aimed to study loudness perception in three participant groups (typically developing children, children using cochlear implants, children using hearings aids) are discussed in terms of loudness growth identification and intensity discrimination. For each of the loudness perception tests (loudness growth identification test & intensity discrimination test), the results are discussed regarding responses for the three warble-tones (500 Hz, 1000 Hz, & 4000 Hz) and three vowels (/u/, /a/, & /i/). For the loudness growth identification test, the effect of stimulus order presentation is initially discussed, followed by the intensity required to perceive specific loudness levels. The latter is done for each of the participant groups as well as across the three groups. Likewise, the findings of the intensity discrimination test are discussed for each of the three participant groups and across the groups.

5.1 Effect of stimulus-order presentation (random & sequential) on intensity required to identify loudness levels

The effect of random and sequential order method on the intensity required to identify loudness levels in the loudness growth identification test was initially studied on the typically developing children and one of the clinical groups (children using cochlear implants). The effect of stimulus order was not studied in children using hearing aids as each child would have to be tested in three different hearing aid conditions (own prescribed, linear, & non-linear), which would have adversely affected the responses of the children due to practice and fatigue.

In the typically developing children, the random and sequential order methods were found to have significant effect on the intensity required to identify specific loudness levels.

This significant difference was found to vary depending on the loudness level as well as the stimulus used. To perceive lower loudness levels (very soft & soft), the children required lesser intensity for the random order of presentation than the sequential order method for most of the stimuli (1000 Hz, 4000 Hz, /u/, & /i/). However, at higher loudness levels (comfortable & loud/too loud), they required more intensity for the random order method than the sequential order method for stimuli in the mid frequency region (1000 Hz & /a/) and high frequency warble-tone (4000 Hz). Thus, the results indicated that in typically developing children, the intensity required to identify extreme loudness levels were affected by the order of stimulus presentation.

On the other hand, in *children using cochlear implants*, the intensity needed to identify specific loudness levels did not vary across the two methods, except for the 1000 Hz warble-tone. Hence, it can be inferred that the order of stimulus presentation did not affect the children using cochlear implants to the same extend that it did in the typically developing children. The absence of a significant different between the methods was also evident from the small Bayes factor, and moderate-to-small effect size. The findings regarding no difference in the two methods in the children using cochlear implants, reflects the responses of only 48% of the children who were able to give consistent, valid responses. More than half the children using cochlear implants were not able to give the required responses, unlike the typically developing children who could all carry out the task.

The difference in responses across the two methods in the typically developing children could reflect their ability to use their cognitive skills, especially when listening to signals that were difficult to judge. While responding to the sequential order, the typically developing children would have used the lower level as a guide to predict the next higher level. In anticipation of a higher presentation level for a subsequent signal presentation, they would have indicated that they heard a higher-level signal. Such a cue to guide them to respond to a subsequent higher level would have been absent when the signals were presented in a random order. Thus, their responses to the random order of presentation would be a true reflection of the intensity required to identify various loudness levels. In literature, Baird et al. (1991) also reported that their participants gave more consistent responses for a random order method than for a sequential order method of stimulus presentation.

Possible reasons as to why the typically developing children had difference in the two methods only at the extreme levels could be due to the difficulty in perceiving auditory cues at these levels. Thus, at these levels they would have had to depend on judgement relative to the earlier presented sound. Baird et al. (1991) was also of the view that for the extreme loudness levels, their participants depended on the loudness of the prior sound to make a judgement of the subsequent sound. It is speculated that the lower-level signals would have been difficult to judge due to issues related to audibility. It has been demonstrated by Rabinowitz et al. (1976) that at low levels discrimination of intensity decreases. This was also apparent in an experiment conducted earlier by Ham and Parkinson (1932), where greater errors in discrimination were observed at lower levels. They ascribed this finding to masking of the lower-level signals by background noise.

Similar to the current study, the effect of stimulus order presentation on loudness growth function in normal hearing participants was studied by Berliner et al. (1977), Beattie et al. (1997), and Jenstad et al. (1997). It was reported by Jenstad et al. (1997) that for low input levels, the sequential order of stimulus presentation led to a slower increase in loudness compared to the random order of stimulus presentation, across frequencies. This indicated that for the sequential order method, at low loudness levels the participants needed more intensity to perceive the loudness similar to that of the random order method. The findings of the present study are in consonance with that of Jenstad et al. (1997). Similar difference in methods only at the extreme loudness levels was also noted in an earlier study by Berliner et al. (1977).   Although, Beattie et al. (1997) reported similar findings as that of the present study at high loudness levels, their findings for the lower levels were different. At the higher presentation levels their participants also required higher sound pressure levels for the random order method than the sequential order method. However, unlike the current study, at the low loudness levels no difference in sound pressure levels was obtained between the two methods of presentation.   The difference between the studies could be on account of individuals differences in performance. Such individual differences in loudness growth have earlier been noted by Marozeau and Florentine (2007). Further, while studies in literature provide reasons for differences in perceiving loudness of softer signals, such explanations for higher levels of stimulus presentation are not mentioned. The children in the present study probably required more intensity at the higher loudness levels for the random order method than the sequential order method to get more cues to make an accurate judgement in the former method. They would not have needed this higher intensity for the sequential order method as they would have used the earlier heard stimuli as a reference to make a loudness judgement, which would not have been possible in the random order method. This could have led to the difference in the two methods.

The children using cochlear implants, unlike the typically developing children in the present study, did not demonstrate a difference in the two methods of stimulus presentation. This possibly was an indication of their lack of cognitive skill of the former group to use an earlier heard stimulus as a reference to make a judgement about the subsequent signal during the sequential order presentation. This would have led to them to use similar strategies when responding to both random and sequential order methods, resulting in similar responses. Despite them using similar response strategies for both methods, the children using cochlear implants, who could give consistent responses, like the typically developing children did indicate that loudness increased when intensity increased.

It can be construed from the present study that either of the methods of stimulus presentation can be used for loudness growth evaluation in children using cochlear implants, as long as they are able to give valid responses. Additionally, it is reported by Baird et al. (1991) that the response variability in the random order method was less in normal hearing listeners. Hence, it is recommended that while evaluating loudness growth in children, a random order method would be the preferred method of evaluation.

Based on the findings of the typically developing children, hypothesis 1a, *"There is no significant difference between random and sequential order methods of stimulus presentation on loudness growth perception in typically developing children",* is partially rejected. However, from the findings of the children using cochlear implants, hypothesis 1b, *"There is no significant difference between random and sequential order methods of stimulus presentation on loudness growth perception in children using cochlear implants",* is partially accepted.

5.2 Comparison of Loudness Perception by Typically Developing Children, Children Using Cochlear Implants, and Children Using Hearing Aids

The comparison of loudness perception by the typically developing children, children using cochlear implants, and children using hearing aids for loudness growth identification as well as intensity discrimination are discussed. The children using hearing aids are compared across the three conditions in which they were tested (own prescribed hearing aids, linear hearing aid setting, & non-linear hearing aid setting).

5.2.1 Comparison of Loudness Growth Identification Across the Three Device Conditions in Children Using Hearing Aids

The results of the loudness growth identification test are discussed for those (65%) who gave consistent, valid responses. It was observed that in general, the intensity required by the participants to identify loudness levels was similar with their *own prescribed hearing aids and the linear hearing aids*. An exception to this was while perceiving 4000 Hz, 'soft' sounds, where they required significantly higher intensity with their own hearing aids compared to the hearing aids with linear setting. Likewise, similar levels were required with their *own hearing aids and non-linear hearing aids*, except to identify 'comfortable' level of mid frequency stimuli (1000 Hz & /a/), where they required lesser intensity with the former devices. Similarly, when the loudness growth identification was compared between the *linear and non-linear hearing aids,* the difference was noted for the mid-frequency stimuli (1000 Hz & /a/). Using non-linear hearing aids, they required more intensity to identify 'comfortable' and 'loud' levels of the mid frequency stimuli than the linear hearing aids. Thus, it can be inferred that the non-linear hearing aids majorly differed from the linear hearing aids only in the mid frequency region. This difference was present even if the hearing aids had less compression, as present in the participants' own hearing aids.

The difference between the non-linear hearing aids when compared to the participant's own as well as linear hearing aids at the mid frequency could probably be due to the effective compression at the mid frequency compared to the low and high frequencies. The effective compression ratio was found to be lesser at low frequencies than at mid and high frequencies by Kuk (1996) and Hornsby and Ricketts (2001). Additionally, the limited benefit at high frequencies through hearing aids, observed by Stelmachowicz et al. (2004) and Turner (2006), could have led to the lack of appropriate experience in children using hearing aids. This could have resulted in no difference in the low and mid frequencies.

The approximate similarity in loudness identification with the participants' own-prescribed hearing aids and the linear hearing aids in the present study could be attributed to similar settings in both. The relatively low compression ratio (~ 1:1.5) used in the own hearing aids of the participants, would have resulted in them having gain similar to the linear hearing aids. This would have resulted in them having almost similar performance. Further, the stimuli in which differences were seen in the 'own and non-linear' hearing aids as well as 'linear and non-linear' hearing aids, had relatively large effect size, indicating that number of participants studied did not influence the findings.

It is possible that if more loudness gradations were used in the loudness growth chart (> 6 gradations), subtle differences in loudness perception may have been obtained across the hearing aid conditions. With the six-gradations that were used in the current study, the participants would have had limited choices to select their response. Thus, minor differences perceived by them may have been missed. The six gradations were selected for the study to reduce the complexity of the task for children with limited listening experience. However, if children do demonstrate fairly good perception of loudness, it is recommended that larger gradations be used while evaluating loudness growth.

The findings of the current study are in line with the observations made by Jenstad et al. (2000), who compared loudness growth functions for linear and non-linear hearing aids. Similar to the current study, they observed a difference in the hearing aids at 1000 Hz at high intensity levels. However, in contrast to the results obtained in the current study, Jenstad et al. (2000) also observed differences for high frequency stimuli at higher loudness levels. This lack of difference observed in the present study for high frequency stimulus could be due to the differences in the age of the participants and their experience in listening to high frequency stimuli. The children in the current study had congenital hearing loss and hence would have had less experience in hearing high frequency stimuli unlike participants in the study by Jenstad et al. (2000). Their participants appeared to have acquired hearing loss as they had used their devices for durations as short as 1 year.

Hence, the following null hypotheses are partially accepted:

2a. "There is no significant difference in loudness growth perception between own hearing aids and linear hearing aids",

2b "There is no significant difference in loudness growth perception between own hearing aids and non-linear hearing aids",

2c. "There is no significant difference in loudness growth perception between linear hearing aids and non-linear hearing aids".

5.2.2 Comparison of Intensity Discrimination Across the Three Device Conditions in Children Using Hearing Aids

The intensity discrimination thresholds of the participants were higher when they wore their *own hearing aids compared to the linear hearing aids* for all stimuli, but were significantly different only at 500 Hz and 4000 Hz. The relatively steeper increase in gain with increase in intensity in the linear hearing aids compared to their own hearing aids could have resulted in the children discriminating smaller intensity differences with the latter compared to the former. The own hearing aids of all the participants had some amount of compression, though relatively less (~1:1.5). The lack of difference in intensity discrimination between the two conditions at 1000 Hz could have been due to the steepness of the loudness curves being similar in this frequency region in the hearing aids. It has been reported by Byrne et al. (2001) that the gain of hearing aids varies as a function of the frequency. The gain was reported to be less steep in the mid frequencies and more in the extreme frequencies. This could have resulted in the intensity discrimination being different only in the extreme frequencies in the present study. The broader frequency range of the vowel formants would have enabled their intensity discrimination to not be influenced by the steepness of the gain of the hearing aids with change in frequency. Thus, the participants may have utilised similar frequency information for all three vowels, resulting in no difference for all the vowels between their own hearing aids and linear hearing aids.

Similar to the current study, the effect of compression in hearing aids on judgement of relative distance of speech stimuli, which is cued by level difference was not found by Akeroyd (2010). The findings were ascribed to less compression ratio in the non-linear hearing aids of the participants, leading them to not notice intensity difference. They also attributed the findings to the good experience of the listeners that would have helped them in relative distance perception.

Unlike what was observed between the participants' own hearing aids and the linear hearing aids, no significant difference in intensity discrimination thresholds occurred between their *own hearing aids and non-linear hearing aids* in the present study. This was seen for both warble-tones and vowels. This probably occurred as in both hearing aid conditions (own hearing aids & non-linear hearing aids) the steepness of the gain with increase in intensity did not differ to the extent to bring about a significant difference in intensity discrimination. This would have resulted in the participants having similar intensity discrimination.

The negative effect of compression on intensity discrimination was noted by Devi et al. (2017), who reported that the intensity discrimination thresholds deteriorated with the use of non-linear hearing aids. Their participants had better intensity discrimination thresholds in the unaided condition, which reduced with the use of WDRC hearing aids. Likewise, in the current study, the intensity discrimination for all stimuli were poorer with the non-linear hearing aids when compared to the other two hearing aid conditions. The intensity discrimination was relatively better with their own hearing aids compared to the ‘test non-linear hearing aids’ as the former had less compression. Thus, it can be construed that as the amount of compression increases, the intensity discrimination becomes poorer.

The comparison between the *non-linear hearing aids and the linear hearing aids,* in the present study indicated that the intensity discrimination thresholds were higher for the former for most of the stimuli, except /u/ and /a/. The high Bayes factor confirmed the presence of a significant difference between the conditions. The absence of compression in the linear hearing aids would have led to the better discrimination thresholds with these devices compared to the non-linear hearing aids as it would have enabled them to perceive smaller changes in intensity. However, in hearing aids with compression (non-linear condition), increase in input intensity would have resulted in no increase or a decrease in output intensity, making it possible for the participants to perceive only larger differences in intensity.

Among the three speech stimuli used in the present study, a difference in discrimination thresholds between linear and non-linear hearing aids was seen only for the high-frequency vowel /i/ and not for the low-frequency vowel /u/, and mid-frequency vowel /a/. This could probably be due to the difference in the formant frequencies of the vowels. It is speculated that as the first two formant frequencies for the vowel /i/ are further apart compared to the vowels /u/ and /a/, the cumulative increase in intensity due to formant proximity would have been less in the former vowel. However, the relative closer proximity of the first and second formats of the vowels /u/ as well as /a/ could have led to an overall increase in intensity in them. This increase in intensity would have counterbalanced the intensity difference that would have occurred due to the presence or absence of compression. Thus, the intensity discrimination of vowels could have been influenced by the proximity of the formant frequencies, thereby having an impact on the significance of difference between the linear and non-linear hearing aids.

Similar to the findings of the current study, Musa-Shufani et al. (2006) also noted that the cue for just noticeable difference in intensity for lateralization increased with an increase in compression ratio. This effect of compression on just noticeable difference was more pronounced for noise centred at 4000 Hz than 500 Hz used in their study.

Thus, it can be constructed from the present study that compression algorithms used in hearing aids could affect the discrimination of intensity as a function of the type and frequency of the stimuli. Intensity discrimination threshold was the least when the participants used linear hearing aids. Hence, it can be inferred that lower levels of compression are less likely to impact intensity discrimination thresholds.

Based on the findings of the current study, the null hypothesis *3a, "There is no significant difference in intensity discrimination between own hearing aids and linear hearing aids"* is partially accepted; the hypothesis 3b, *"There is no significant difference in intensity discrimination between own hearing aids and non-linear hearing aids"* is accepted; and the hypothesis *3c, "There is no significant difference in intensity discrimination between linear hearing aids and non-linear hearing aids"* is partially rejected.

5.2.3 Comparison of Loudness Growth Identification Between Typically Developing Children, Children using Cochlear Implants and Children using Hearing Aids

It was noted in the current study that 52% of the participants using cochlear implants were not able to perform the loudness growth task accurately. Among those who gave consistent responses, the intensity required to identify loudness levels by the *typically developing children and children using cochlear implants* did not show any significant differences, except at the 'very soft' and 'soft' loudness levels, when measured using Mann-

Whitney U test. At the ‘very soft’ loudness level, for all the stimuli and the ‘soft’ level for 4000 Hz, the children using cochlear implants required more intensity to perceive the loudness like the typically developing children. This was consistent across all the six stimuli.

The differences in intensity between the two groups at the low loudness levels could be due to inadequate signal level through cochlear implants, making it difficult for the children using these devices to hear them. On the other hand, at the higher presentation levels, the loudness growth in the children using cochlear implants was probably similar to that of the typically developing children, resulting in no difference in the two groups of children. This indicates that loudness growth in children using cochlear implants is less steep at lower intensity levels compared to the typically developing children. The former group required more intensity to perceive softer signals similar to that of typically developing children. Thus, the findings of the present study indicate that a large number of children using cochlear implants are unable to accurately perceive loudness growth of signals. Among the few who were able to give accurate responses, their loudness growth was majorly similar to that of the typically developing children, especially for louder signals.

Like the current study, in literature loudness growth functions of cochlear implant users was noted to be similar as that of normal hearing individuals (Busby & Au, 2017; Steel et al., 2014). However, unlike the present study, they found no differences in the two groups for the softer loudness levels. In both the studies reported in literature, the comparison of loudness growth was done with electrical charge in cochlear implant users and acoustical stimuli in normal hearing listeners. Where as in the present study both participant groups were assessed using acoustical stimuli. This might have resulted in the difference in the lower levels between the current study and the studies by Steel et al. (2014) and Busby and Au (2017). Further, Kordus and Żera (2017) who used acoustical stimuli also did not find significant difference in the slope coefficients between normal hearing participants and those using Cochlear Corporation cochlear implants. However, those using Advanced Bionics implants had slope coefficients that were different from normal hearing participants. These loudness growth function slope coefficients were calculated with the lines fitted to the mid-to-high level range where the largest linear segments occurred and the lines were not fitted for the lower levels due to large inter-subject variability. Thus, the slopes calculated by Kordus and Żera (2017) mainly focused on the mid to higher levels. Like the present study, their findings also indicated that children using cochlear implants do not differ from typically developing children at these levels.

As similar responses were seen between the typically developing children and the children using cochlear implants in the present study, it can be construed that the sequential order method of loudness growth identification can be reliably used. However, in the latter group this can be done only on those who give consistent responses, as close to 50% of the participants using cochlear implants in the current study were unable to give valid responses. Thus, prior to evaluating loudness growth identification in children using cochlear implants, it is recommended that clinicians first determine whether children give consistent responses. This could be done using either a random order presentation or a sequential order presentation of stimuli.

Additionally, the discriminant function analysis done in the current study to determine the parameters that differentiated the three groups, revealed that children could be differentiated depending on the group with which they were combined. The children using cochlear implants could be differentiated from the typically developing children only when grouped with children using non-linear hearing aids. However, when grouped with the hearing aid users wearing their own-prescribed hearing aids, where relatively lesser compression was used, or them wearing linear hearing aids, the two groups (cochlear implant vs typically developing) could not be differentiated to the same extent. This probably was due to the way the responses of the three groups interacted when combined with those using more compression versus less to no compression. Only a limited number of parameters differentiated the children using cochlear implants from the typically developing children (4000 Hz, soft; /a/, comfortable; 4000 Hz, loud; & /u/, soft).

The comparison of loudness growth identification between the *typically developing children and children using hearing aids* indicated that depending on the hearing aid condition (own prescribed, linear, or non-linear), the difference between the two groups varied marginally. This was observed when difference was measured using Mann-Whitney U test. For all three hearing aid conditions and six stimuli, the difference between the two groups mainly existed for the softer stimuli, with those using amplification requiring significantly more intensity. However, differences were seen between the two groups for higher levels of presentation when the children using hearing aids wore the linear as well as non-linear ‘test hearing aids’. This difference was mainly seen for the 500 Hz warble-tone and not for the other stimuli. Further, similar to the children using cochlear implants, many children using hearing aids also failed to give consistent loudness growth identification responses. Only 65% of the children using hearing aids were able to give valid responses.

The higher intensity required at low loudness level by the children wearing hearing aids could be due to inadequate audibility, making it difficult for them to make decision. However, at higher levels, in general the participants using hearing aids could perceive the loudness similar to typically developing children. This indicates that loudness growth in children using hearing aids was similar to that of typically developing children. This was especially seen when the hearing aid users either wore their own hearing aids that had slight compression or wore the ‘test hearing aids’ with non-linear setting. However, at 500 Hz with the ‘test hearing aids’ with linear setting, the hearing aid users required higher intensity to perceive loudness similar to the typically developing children. This could be an indication that at this frequency the linear hearing aids had inadequate gain, making it necessary that higher intensity be provided for these children to perceive each of the loudness levels.

The findings of the present study, where generally more intensity was needed by those using hearing aids for the perception of soft loudness levels compared to the normal hearing participants, are consistent with that reported in literature (Gottermeier & De Filippo, 2018; Scollie et al., 2010; Shi et al., 2007). Similar to the current study, Gottermeier and De Filippo (2018) also noted that most of their participants using non-linear hearing aids required stronger signals at low levels to perceive loudness similar to that of normal hearing listeners. Further, Scollie et al. (2010) also found that children using newly fitted non-linear hearing aids had poorer sensitivity at low loudness levels than their normal hearing participants. Additionally, Shi et al. (2007) noted that at 2000 Hz, loudness growth function for those using hearing aids had shallower function than normal hearing listeners. Conversely, at 500 Hz the loudness growth function for the hearing aid users was steeper than their normal hearing listeners. Jenstad et al. (2000) noted that the loudness growth function for the adults using linear hearing aids was close to the function of normal hearing individuals at low intensity levels, but was different at high loudness levels. However, these findings were not statistically analysed.

From the discriminant function analysis done in the present study to differentiate the participant groups, the children using hearing aids could be differentiated from the typically developing children irrespective of the hearing aid conditions (own prescribed, linear & non-linear hearing aids). However, the factors that differentiated them from the typically developing children varied depending on the hearing aid condition (Table 4.35). This indicates that the difference in gain of the hearing aids as a function of change in intensity affected the parameters (stimuli / loudness level) that differentiated the children. More parameters differentiated the typically developing children from the children using hearing aids when they used their own devices, than when they used the test hearing aids with relatively higher levels of compression (non-linear) or no compression (linear).

The comparison of loudness growth identification between *children using cochlear implants and children using hearing aids* indicated that there was no significant difference in the intensity required to perceive loudness between them. An exception to this was at 4000 Hz to perceive ‘very soft’ and ‘soft’ loudness levels where the hearing aid users needed higher intensities when they used their own prescribed hearing aids or when they used non-linear hearing aids.

The general lack of difference in intensity required to identify loudness levels between the two groups could be a reflection of the similarity in the effect of compression available in the hearing aids and cochlear implants. However, with the use of compression (own hearing aids & non-linear hearing aids), differences occurred between the two groups for softer high frequency signals. The difference between the compression available in hearing aids and cochlear implants for low level high frequency warble-tone could have resulted in the difference between the two groups. A possible reason for such a difference not being observed for the high frequency vowel /i/, was because of its low frequency first formant, enabling its loudness to be perceived like other low frequency stimuli. At higher levels, the children probably did not depend on the compression of the device to perceive the loudness levels as no significant difference occurred between the cochlear implant users and hearing aid users, irrespective of whether they wore linear or non-linear hearing aids.

The discriminant function analysis carried out in the present study confirmed that children using cochlear implants were differentiated for the hearing aid users only when the latter group wore the ‘test hearing aids’ with non-linear setting. This indicates that the higher compression used in the non-linear hearing aids, helped differentiate them when the data of all three groups were compared. The loudness growth perception of the cochlear implant users cannot be differentiated from hearing aid users who wore devices with lesser compression (own hearing aid) or no compression (linear hearing aid).

Thus, the null hypotheses 4*a. "There is no significant difference in loudness growth perception between typically developing children, children using cochlear implants and children using own prescribed hearing aids",*4b*. "There is no significant difference in loudness growth perception between typically developing children, children using cochlear implants and children using hearing aids with linear setting"*; and 4c, *"There is no significant difference in loudness growth perception between typically developing children, children using cochlear implants and children using hearing aids with non-linear setting",* are partially accepted.

5.2.4 Comparison of Intensity Discrimination Between Typically Developing Children, Children using Cochlear Implants and Children using Hearing Aids

The intensity discrimination thresholds between *typically developing children and children using cochlear implants* were significantly poorer in the latter group compared to the former group for the warble-tone 500 Hz and 4000 Hz. Likewise, they had poorer intensity discrimination thresholds for the vowels /u/ and /a/. The poorer discrimination thresholds in the children using cochlear implants could either be due to the inability of the auditory pathway to detect minor changes in intensity or due to their device not having the capacity to process finer changes in intensity. It has been reported in literature that poorer spiral ganglion cell count was observed in those with hearing loss with it being more with those having the problem for longer duration and higher degree (Nadol et al., 1989). This could have resulted in poorer sensitivity to loudness change in children using cochlear implants compared to the typically developing children.

A possible reason why children using cochlear implants performed poorer than the typically developing children for the low (/u/) and mid frequency (/a/) vowels could be due to the structure of their formants. As can be seen in Figure 3.1, the first two formant frequencies of the vowels /u/ and /a/ were relatively closer than that of the vowel /i/. This would have resulted in the stimulation of electrodes that were closer for the vowels /u/ and /a/ compared to the vowel /i/. It is possible that due to the proximity of the electrodes being stimulated for the vowels /u/ and /a/, the cochlear implant users would have perceived these stimuli as being louder than the vowel /i/. This may have resulted in them having higher intensity discrimination thresholds for /u/ and /a/ compared to /i/ (Figure 4.11). While a similar effect may have occurred in the typically developing children, the variations in intensity discrimination across vowels was not to the same extent as that seen in the children using cochlear implants. This would have resulted in a significant difference between the two groups for the former two vowels and not for the latter vowel.

The higher intensity discrimination thresholds observed in the children using cochlear implants compared to typically developing children seen in the present study is consistent with the findings of Saki et al. (2015) and Tak and Yathiraj (2019a). However, differences exist in terms of the frequencies in which the two groups differed. Saki et al. (2015) reported poorer intensity discrimination for warble-tones having frequencies of 500 Hz, 1 kHz, 2 kHz, and 4 kHz, whereas Tak and Yathiraj (2019a) observed differences at 4 kHz and the vowels /a/ and /u/. The heterogeneity seen in individuals with hearing loss could have led to variations across the studies.

The comparison between the *typically developing children and children using hearing aids* in the current study indicated that when the latter group wore devices with compression (own prescribed hearing aids & non-linear hearing aids), their warble-tone thresholds were poorer than the former group. However, when they wore linear hearing aids, the difference was present only for the 1000 Hz warble-tone. Unlike what was observed for the warble-tones, for vowels the children using hearing aids obtained poorer discrimination thresholds for /u/, irrespective of the type of hearing aid they wore (own with minimal compression, linear, or non-linear hearing aids). On the other hand, when non-linear hearing aids were used, the difference was also obtained for the other two vowels (/a/ & /i/). As mentioned regarding the children using cochlear implants, the poorer thresholds observed in the children using hearing aids could be a display of either the poor processing ability of their auditory pathway or the inability of their device to adequately let them perceive intensity discrimination. However, it is speculated that the main reason that they had difficulty in intensity discrimination probably was majorly on account of the device rather than just a problem in their auditory pathway. The compression in the hearing aids would have made it difficult for the children to differentiate loudness, as an increase in input intensity would not have resulted in a corresponding increase in output intensity. Further, the poor intensity discrimination with the vowel /u/ could be due to its low first and second formants frequencies. As reported by studies in the literature, at low frequency the rate of loudness growth is rapid in normal hearing individuals (Hellman & Zwislocki, 1968; Suzuki & Takeshima, 2004). However, as was explained by Davis (1983), the active mechanism at the apical region responsible for rapid loudness growth at low frequency is affected in those with a hearing loss. This would have led to poorer intensity discrimination thresholds for the low frequency vowel /u/, which has an F1 frequency that is lower than 500 Hz (Raphael et al., 2007). On account of this the children using hearing aids would have had difficulty with the vowel /u/, with all three types of hearing aids.

These findings in the current study are in consonance with that of Musa-Shufani et al. (2006) who noted that level discrimination, which was a cue for directional hearing in the horizontal plane, deteriorated with the increase in compression ratio. On the other hand, Whitmer and Akeroyd (2011) noted that the sensitivity to level difference had no relation with hearing aid compressions between 1.2 and 2:1. Similarly, Akeroyd (2010) did not find any effect of compression ratio on the just noticeable difference in distance. The authors speculated that the findings could have been affected due to the acclimatization effect of hearing aids on level. The difference in findings of Whitmer and Akeroyd (2011) and Akeroyd (2010) from the current study could be due to differences in stimuli used as well as the measure used to determine intensity discrimination.

The comparison of intensity discrimination in the present study between *children using cochlear implants and children using hearing aids* revealed that there was no significant difference between the two groups for most stimuli (3 warble-tones & 3 vowels) and hearing aid conditions (own with minimal compression, linear, or non-linear hearing aids). The children using cochlear implants had significantly poorer thresholds compared to the children using linear hearing aids only for the 4000 Hz warble-tone. However, they had significantly better thresholds than those using non-linear hearing aids only for the 1000 Hz warble-tone and vowel /i/.

The lack of difference between the two clinical groups for most stimuli probably indicates that the different sets of devices had similar properties that enabled the children to obtain comparable intensity discrimination cues. These findings can occur provided the intensity discrimination is carried out with signals that are adequately audible. It has been noted by Tak and Yathiraj (2021) that no significant difference occurred in relative loudness judgement between children using hearing aids and children using cochlear implants. Thus, like relative loudness judgement, children using cochlear implants and those using hearing aids had similar intensity discrimination abilities. However, Most and Peled (2007) reported that children using cochlear implants had significantly poorer perception of stress than children using hearing aids. For stress perception, besides intensity cues, duration and frequency cues are also reported to be utilised (Fry, 1955; Kumar & Bhat, 2009; Lieberman, 1960). It is possible that the participants in the study by Most and Peled (2007) made use of cues other than intensity to perceive stress, leading to a difference between those using cochlear implants and hearing aids.

Therefore, the null hypotheses 5a. *"There is no significant difference in intensity discrimination between typically developing children, children using cochlear implants and children using own prescribed hearing aids"*; and 5b. *"There is no significant difference in intensity discrimination between typically developing children, children using cochlear implants and children using hearing aids with linear setting",* are partially rejected; While the null hypothesis 5c. *"There is no significant difference in intensity discrimination between typically developing children, children using cochlear implants and children using non-linear hearing aids",* is partially accepted.

From the overall findings in the present study, it can be construed that loudness perception in children using cochlear implants as well as children using hearing aids is poorer than that of typically developing children. The loudness growth identification across the three groups varied in terms of the stimuli, the loudness levels, and the device type. Likewise, intensity discrimination tended to be poorer in the two clinical groups compared to the typically developing group. Among the hearing aid users, this difference was more prominent when the children wore hearing aids with compression (own hearing aids or non-linear hearing aids). However, the two clinical groups differed only for a few stimuli.

6. Summary and Conclusion

Loudness perception is reported to be poor in those with sensorineural hearing loss (Al-Salim et al., 2010; Brand & Hohmann, 2001; Buus & Florentine, 2002; Hellman & Meiselman, 1993; Plack et al., 2004; Robinson & Gatehouse, 1996; Serpanos & Gravel, 2000, 2004). Loudness perception in those with hearing loss was found to be not comparable to those with normal hearing even with the use of hearing aids (Gatehouse et al., 2006; Jenstad et al., 2000; Moore, 1996; Musa-Shufani et al., 2006; Shi et al., 2007). Studies have demonstrated that both loudness growth perception (Gottermeier & De Filippo, 2018; Jenstad et al., 2000; Shi et al., 2007) as well as intensity discrimination (Devi et al., 2017; Musa-Shufani et al., 2006; Robinson & Gatehouse, 1995; Whitmer & Akeroyd, 2011) were affected in hearing aid users. Similarly, loudness perception was noted to be adversely affected in those using cochlear implants (Anzalone & Smith, 2017; Kordus & Żera, 2017; Saki et al., 2015; Steel et al., 2014). In those using cochlear implants, the majority of studies have evaluated loudness perception to electrical stimuli (Anzalone & Smith, 2017; Bierer & Nye, 2014; Busby & Au, 2017; Chatterjee, 1999; Chatterjee et al., 2000; Nelson et al., 1996; Steel et al., 2014; Zeng & Shannon, 1994). Relatively few studied have assessed loudness perception for acoustical stimuli (Kordus & Żera, 2017; Saki et al., 2015; Tak & Yathiraj, 2019a). Additionally, loudness perception through listening devices in those having hearing loss has mainly been studied in adults with acquired hearing loss (Anzalone & Smith, 2017; Bierer & Nye, 2014; Busby & Au, 2017; Chatterjee, 1999; Chatterjee et al., 2000; Kordus & Żera, 2017; Saki et al., 2015; Steel et al., 2014; Zeng & Shannon, 1994) and studies on children are sparse (Tak & Yathiraj, 2019a, 2019b, 2021).

The current study was conducted with the aim of comparing loudness perception in children using hearing aids, children using cochlear implants, and typically developing children. Loudness growth identification and intensity discrimination were evaluated in 20 children using hearing aids and 25 children using monaural cochlear implants. The performances of these clinical groups were compared with each other as well as with 31 typically developing children. Further, the study also evaluated the effect of compression parameters on loudness perception in the children using binaural hearing aids for loudness growth identification as well as intensity discrimination in three hearing aid conditions. The conditions included testing the children while wearing their ‘own prescribed hearing aids’, ‘test hearing aids’ in linear setting, and ‘test hearing aids’ in non-linear setting. While the non-linear hearing aids had a compression ratio of 3.1:1, the participants’ own hearing aids had relatively less compression.

The loudness growth identification test and intensity discrimination were evaluated using three warble-tones (500 Hz, 1000 Hz, & 4000 Hz) and three vowels (/u/, /a/, & /i/). The children heard the stimuli presented from a computer through a loudspeaker kept at 0° azimuth at a distance of 1 meter from their head.

Loudness growth identification was initially tested using two methods (random order method & sequential order method) to determine the effect of order of stimulus presentation. This was done on the typically developing children and the children using cochlear implants. The participants had to judge the loudness level on a loudness growth chart having six-loudness categories. It was established that both methods were similar in the children using cochlear implants, but in the typically developing children the intensity required to identify extreme loudness levels were affected by the order of stimulus presentation. Further, as Baird et al. (1991) had noted that response variability in the random order method was less in normal hearing listeners, this method was selected for evaluating the children using hearing aids.

Intensity discrimination was measured with the same stimuli utilised to evaluate loudness growth identification through an adaptive tracking procedure. The intensity of the anchor signal was maintained at 50 dB HL and the variable tone was changed in 5 dB / 2 dB steps. The responses were obtained using a three-alternative forced choice method, where the interval with the louder signal had to be selected.

On the loudness growth identification test, only 12 of the 25 children using cochlear implants (48%) and 13 out of 20 children using hearing aids (65%) gave valid responses. All the typically developing children gave valid responses. The data were analysed only for those who gave valid responses. However, for the intensity discrimination test the data were analysed for all the participants.

Non-parametric statistics were conducted as the data were not normally distributed. To establish if loudness growth identification differed significantly between the three hearing aid conditions (own prescribed hearing aids, linear hearing aids, & non-linear hearing aids), Friedman tests were conducted for each of the six loudness levels. Further, to determine which of the hearing aid conditions differed from each other, Wilcoxon signed-rank test was administered for each stimulus and each loudness level. Similarly, difference in intensity discrimination between the three hearing aid conditions was calculated using Friedman test, followed by Wilcoxon signed-rank test.

The three participant groups (typically developing children, children using cochlear implants, & children using hearing aids) were compared in three different conditions. The three conditions varied with reference to the hearing aids worn by the children using amplification (own-prescribed hearing aids, linear hearing aids, & non-linear hearing aids). The comparison was done between the three groups using Kruskal-Wallis test, followed by Mann-Whitney U test. This comparison was done for both loudness growth identification as well as intensity discrimination. These results were cross-validated using Bayesian statistics. Additionally, to determine which of the stimuli and the loudness levels of the loudness growth identification test differentiated the three groups from each other, canonical discriminant analysis was also conducted.

The findings of the study were as follows:

- *Loudness growth identification for own-prescribed vs. linear vs. non-linear hearing aids*: Among the children using hearing aids, there was no significant difference in loudness growth identification between the three hearing aid conditions, except between linear and non-linear settings at louder levels of 1000 Hz. This indicated that compression had limited effect on loudness growth identification in children using hearing aids.
- *Intensity discrimination for own-prescribed vs. linear vs. non-linear hearing aids*: The intensity discrimination thresholds were significantly better with ‘test hearing aids’ with linear setting compared to the participants’ own-prescribed hearing aids for 500 Hz and 4000 Hz stimuli. The former device also resulted in significantly better thresholds than the ‘test hearing aids’ with non-linear setting for 500 Hz, 1000 Hz, 4000 Hz, and /i/. No significant difference was obtained between the thresholds of the children using their own-prescribed hearing aids and them using ‘test hearing aids’ with non-linear settings. Thus, with the use of compression in hearing aids, intensity discrimination ability reduced.
- *Loudness growth identification between typically developing children and children using cochlear implants*: The children using cochlear implants had significantly poorer loudness growth identification than the typically developing children, majorly at low intensities. These findings indicated that children using cochlear implants

could perceive loudness growth like typically developing children for mid to higher intensity levels, but not for low levels.

- *Intensity discrimination between typically developing children and children using cochlear implants*: The children using cochlear implants obtained significantly poorer discrimination thresholds than the typically developing children for 500 Hz and 4000 Hz warble-tones and for the low (/u/) and mid-frequency (/a/) vowels. The findings indicated that intensity discrimination was difficult for cochlear implant users.
- *Loudness growth identification between typically developing children and children using hearing aids*: The children using hearing aids also had significantly poorer loudness growth identification than the typically developing children mainly at low intensities. The results indicated that except at low intensities, the loudness growth identification was similar in the two groups.
- *Intensity discrimination between typically developing children and children using hearing aids*: Compared to the typically developing children the discrimination thresholds of those using their own-prescribed hearing aids were significantly poorer for all the warble-tones and for the low-frequency vowel /u/. Those using linear hearing aids got significantly poorer discrimination thresholds than the typically developing children for the 1000 Hz warble-tone and the low-frequency vowel /u/. The children using non-linear hearing aids obtained significantly poorer thresholds than the typically developing children for all three warble-tones as well as all three vowels. The findings indicated that with increase in compression in hearing aids, the intensity discrimination ability deteriorated.
- *Loudness growth identification between children using cochlear implants and children using hearing aids*: There was no significant difference between children using cochlear implants and children using linear hearing aids. However, the children

using cochlear implants had significantly better loudness growth identification than the children using their own-prescribed hearing aids as well as children using non-linear hearing aids at low intensities for the high frequency warble-tone. However, for vowels, no significant difference was noted between the two groups. These findings indicated that the loudness growth identification in children using hearing aids was poorer than children using cochlear implants only at high frequencies.

- *Intensity discrimination between children using cochlear implants and children using hearing aids*: No significant difference was observed between children using cochlear implants and the children using their own-prescribed hearing aids. The thresholds of children using linear hearing aids were significantly poorer than the children using cochlear implants only at 4000 Hz. However, for vowels, no significant difference was noted. Compared to non-linear hearing aids, children using cochlear implants obtained significantly better thresholds for the 1000 Hz warble-tone and high-frequency vowel /i/. Thus, in general, not much difference in intensity discrimination occurred between cochlear implant users and those using hearing aids, irrespective of the compression.

From the overall findings it was obtained that loudness perception was poorer for children using hearing aids and children using cochlear implants than typically developing children. Loudness growth identification as well as intensity discrimination varied between the three groups as function of stimulus, loudness level, and also device being used. Among hearing aid users, the loudness perception was affected to a greater extend with compression used in the device. However, the groups using cochlear implants and hearing aids differed from each other only for a few stimuli.

Implications of the study:

The implications of the study are as follows:

- The study highlights the differences in loudness perception between typically developing children, children using hearing aids, and children using cochlear implants.
- The study indicates that many of the children using listening devices (hearing aids & cochlear implants) are unable to perceive loudness cues.
- Insight regarding the way compression parameters impair the loudness perception in those using hearing aids is provided in the study.
- The outcome of the current study indicates that caution should be taken when measuring loudness growth in hearing aid users and cochlear implant users.
- For children using cochlear implants, either random order method or sequential order method of stimulus presentation can be used for loudness growth measurement.
- The study highlights that with more compression in hearing aids, intensity discrimination reduces.

Future directions:

- Further research requires to be done using stimuli such as words and sentences to generalize the loudness perception difficulties of children using cochlear implants and children using hearing aids. Such information will give insight to difficulties faced in real life situations.
- Research where specific map parameters in cochlear implants such as varying the comfort level or the input dynamic range, would shed light on their role in loudness perception in children using cochlear implants.

- Intensity discrimination needs to be studied with the anchor stimulus having different intensity. This would give a better idea about the intensity level wherein compression starts affecting the loudness perception.
- Loudness growth identification in children using listening devices could be checked with larger number of loudness intervals to compare the slope of loudness growth function across those with different degrees of hearing impairment / devices with specific compression levels.

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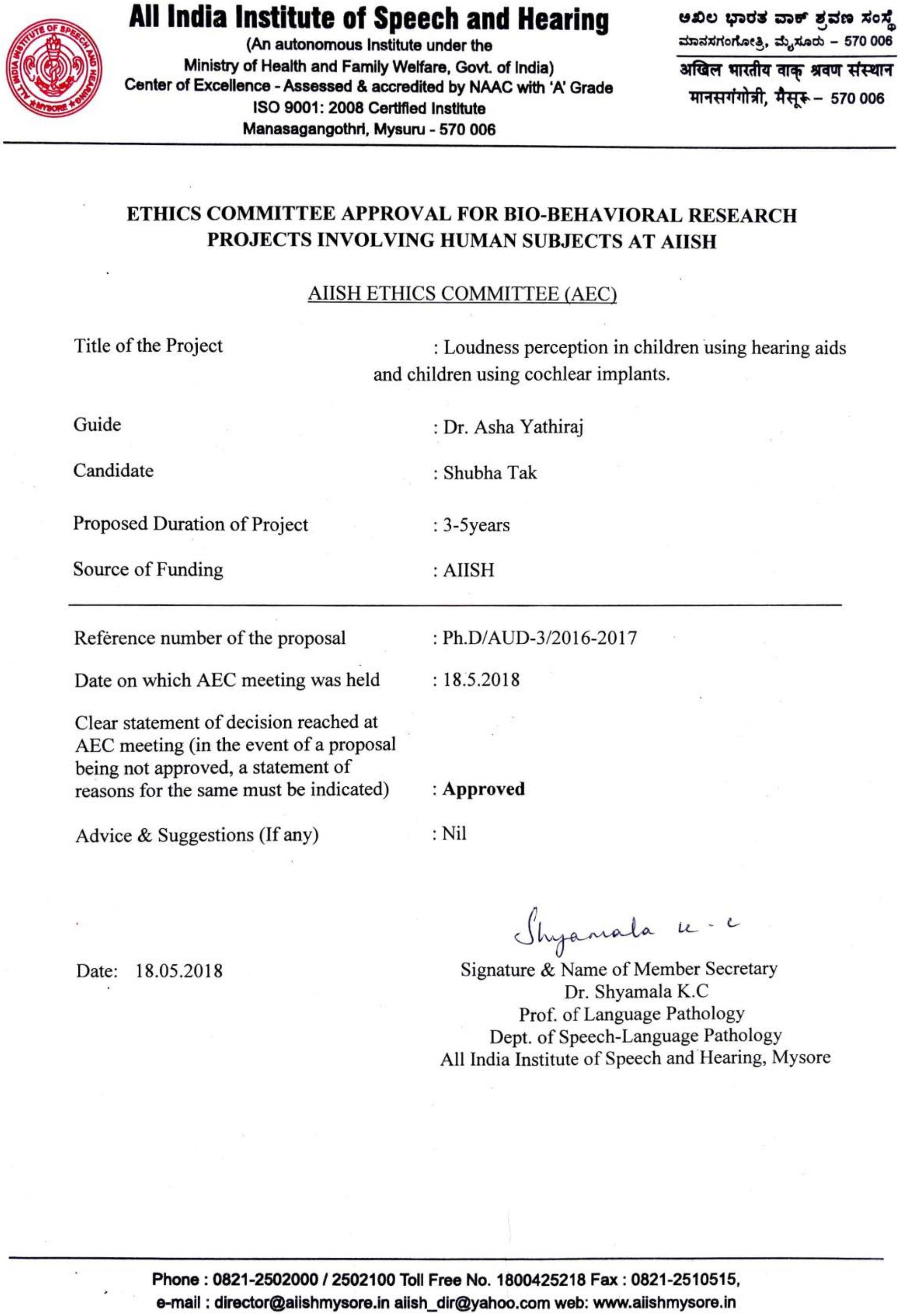
Appendix 1

Ethics committee approval letter



All India Institute of Speech and Hearing
(An autonomous Institute under the
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Center of Excellence - Assessed & accredited by NAAC with 'A' Grade
ISO 9001: 2008 Certified Institute
Manasagangothri, Mysuru - 570 006

ಅಖಿಲ ಭಾರತ ವಾಕ್ ಶ್ರವಣ ಸಂಸ್ಥೆ
ಮಾನಸಗಂಗೋತ್ರಿ, ಮೈಸೂರು – 570 006
अखिल भारतीय वाक् श्रवण संस्थान
मानसगंगोत्री, मैसूरु – 570 006

ETHICS COMMITTEE APPROVAL FOR BIO-BEHAVIORAL RESEARCH PROJECTS INVOLVING HUMAN SUBJECTS AT AIISH

AIISH ETHICS COMMITTEE (AEC)

Title of the Project : Loudness perception in children using hearing aids and children using cochlear implants.

Guide : Dr. Asha Yathiraj

Candidate : Shubha Tak

Proposed Duration of Project : 3-5years

Source of Funding : AIISH

Reference number of the proposal : Ph.D/AUD-3/2016-2017

Date on which AEC meeting was held : 18.5.2018

Clear statement of decision reached at AEC meeting (in the event of a proposal being not approved, a statement of reasons for the same must be indicated) : **Approved**

Advice & Suggestions (If any) : Nil

Shyamala K. C

Date: 18.05.2018

Signature & Name of Member Secretary
Dr. Shyamala K.C
Prof. of Language Pathology
Dept. of Speech-Language Pathology
All India Institute of Speech and Hearing, Mysore

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Appendix 2.

Response sheet

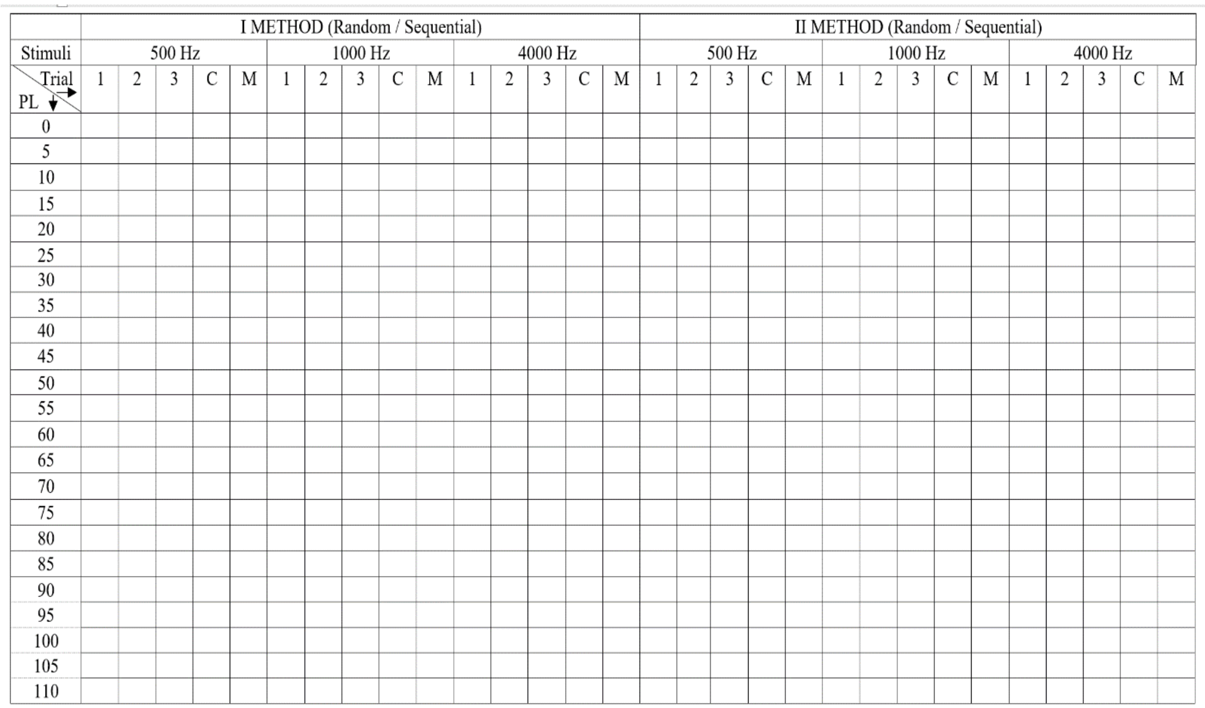
LOUDNESS GROWTH IDENTIFICATION TEST

Case Number:

Name:

Age / Gender:

	Warble-tones		
Tests	500 Hz	1000 Hz	4000 Hz
Thresholds (dB HL)			
Uncomfortable loudness level (dB HL)			



	I METHOD (Random / Sequential)															II METHOD (Random / Sequential)														
Stimuli	500 Hz					1000 Hz					4000 Hz					500 Hz					1000 Hz					4000 Hz				
Trial → PL ↓	1	2	3	C	M	1	2	3	C	M	1	2	3	C	M	1	2	3	C	M	1	2	3	C	M	1	2	3	C	M
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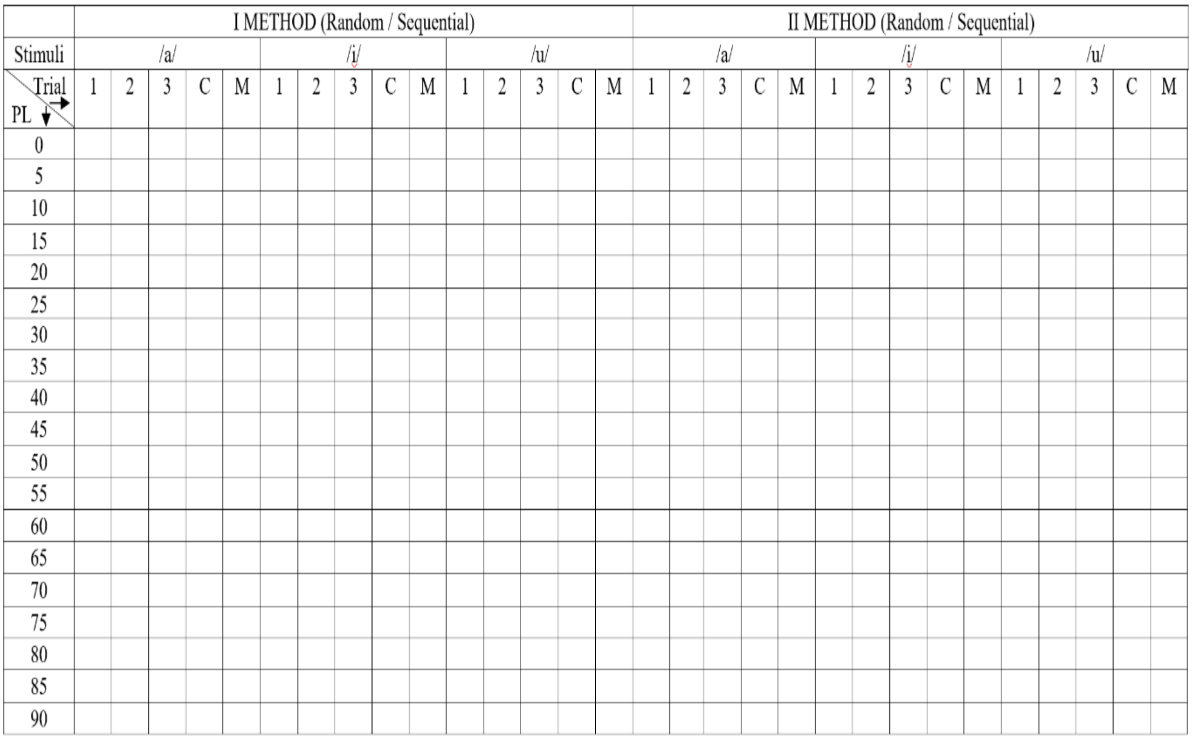
Note: PL = Presentation level; C = Consistency across three trials; M = Median of three trials

Tests	Vowels		
	/a/	/i/	/u/
Thresholds (dB HL)			
Uncomfortable loudness level (dB HL)			



	I METHOD (Random / Sequential)															II METHOD (Random / Sequential)														
Stimuli	/a/					/i/					/u/					/a/					/i/					/u/				
Trial → PL ↓	1	2	3	C	M	1	2	3	C	M	1	2	3	C	M	1	2	3	C	M	1	2	3	C	M	1	2	3	C	M
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Note: PL = Presentation level; C = Consistency across three trials; M = Median of three trials

Appendix 3.

Levels of significance for Shapiro-Wilks test of normality for each intensity level in the typically developing children

Stimulus	Order of presentation	*p*-values for each loudness level				
		Very soft	**Soft**	**Comfortable**	**Loud**	**Too loud**
500 Hz	Random	0.09	0.009**	0.313	0.02*	0.01**
	Sequential	0.16	0.002*	0.13	0.26	0.001***
1000 Hz	Random	0.09	0.4	0.2	0.15	0.08
	Sequential	0.85	0.05	0.02*	0.61	0.2
4000 Hz	Random	0.05	0.1	0.15	0.49	0.01**
	Sequential	0.30	0.36	0.72	0.44	0.03*
/u/	Random	0.62	0.03*	0.14	0.05	0.008**
	Sequential	0.23	0.19	0.08	0.09	0.003**
/a/	Random	0.56	0.08	0.30	0.16	0.07
	Sequential	0.15	0.14	0.03*	0.16	< 0.001***
/i/	Random	0.46	< 0.001***	0.28	0.18	0.02*
	Sequential	0.43	0.67	0.11	0.04*	< 0.001***

Note. * = $p < 0.05$; ** = $p < 0.01$; *** = $p < 0.001$.

Appendix 4.

Levels of significance for Shapiro-Wilks test of normality for each intensity level in the children using cochlear implants

Stimulus	Order of presentation	*p*-values for each loudness level				
		Very soft	**Soft**	**Comfortable**	**Loud**	**Too loud**
500 Hz	Random	0.54	0.47	0.07	0.17	0.08
	Sequential	0.97	0.32	0.20	0.55	0.001**
1000 Hz	Random	0.81	0.37	0.99	0.6	0.001**
	Sequential	0.95	0.62	0.69	0.58	0.89
4000 Hz	Random	0.009**	0.20	0.17	0.40	0.07
	Sequential	0.42	0.05	0.08	0.08	0.09
/u/	Random	0.83	0.68	0.82	0.28	--$^{\#}$
	Sequential	0.48	0.74	0.52	0.34	--
/a/	Random	0.31	0.24	0.04*	0.10	0.27
	Sequential	0.45	0.80	0.95	0.18	--$^{\#}$
/i/	Random	0.42	0.01*	0.15	0.07	--$^{\#}$
	Sequential	0.41	0.78	0.88	0.14	0.81

Note. * = $p < 0.05$; ** = $p < 0.01$; *** = $p < 0.001$; $^{\#}$ = not measured as very few participants chose the loudness level

Appendix 5.

Levels of significance for Shapiro-Wilk test of normality on intensity levels for each loudness levels on children using hearing aids (using prescribed settings in own hearing aids, linear setting & non-linear setting in test hearing aids).

Stimulus	***Group***	***p-value***				
		Very soft	**Soft**	**Comfortable**	**Loud**	**Too loud**
500 Hz	Prescribed	0.24	0.03*	0.17	0.84	0.03*
	Linear	0.79	0.09	0.53	0.45	0.001**
	Non-linear	0.65	0.45	0.008**	0.43	--$^{\#}$
1000 Hz	Prescribed	0.65	0.42	0.11	0.22	0.02*
	Linear	0.48	0.80	0.32	0.38	0.82
	Non-linear	0.21	0.19	0.52	0.73	--$^{\#}$
4000 Hz	Prescribed	0.49	0.31	0.95	0.10	0.31
	Linear	0.27	0.65	0.88	0.32	0.97
	Non-linear	0.27	0.16	0.25	0.09	--$^{\#}$
/u/	Prescribed	0.13	0.08	0.15	0.57	--$^{\#}$
	Linear	0.16	0.70	0.58	0.62	--$^{\#}$
	Non-linear	0.62	0.12	0.27	0.28	--$^{\#}$
/a/	Prescribed	0.28	0.36	0.98	0.04*	0.12
	Linear	0.63	0.08	0.20	0.09	--$^{\#}$
	Non-linear	0.57	0.99	0.60	0.005**	--$^{\#}$
/i/	Prescribed	0.38	0.04*	0.20	0.008**	--$^{\#}$
	Linear	0.12	0.27	0.56	0.81	1
	Non-linear	0.24	0.97	0.07	0.29	< 0.001***

Note. * = $p < 0.05$; ** = $p < 0.01$; *** = $p < 0.001$; $^{\#}$ = Not measured as very few participants chose the loudness level

Appendix 6.

Levels of significance for Shapiro-Wilks test on intensity discrimination for typically developing children, children using cochlear implants and children using hearing aids (using prescribed settings in own hearing aids, linear setting & non-linear setting in test hearing aids).

Group → / Stimuli ↓	***TDC***	***Cochlear implants***	***Hearing aids***		
			Own	***Linear***	***Non-linear***
500 Hz	.13	.36	.75	.05	.50
1000 Hz	.05	.01**	.14	.34	.88
4000 Hz	.42	.00***	.12	.26	.41
/u/	.00***	.10	.39	.11	< .001***
/a/	.10	.01**	.02*	.001**	.65
/i/	.03*	.01**	.05	.01*	.71

Note. * = $p < 0.05$; ** = $p < 0.01$; *** = $p < 0.001$; TDC = Typically developing children