Effect of Jaw Opening on the Speech and Voice of Normal-Hearing and Hearing-Impaired Children: An Acoustic and Physiological Study

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Abstract

This study utilises instrumental measures to examine the effect of jaw opening on the speech and voice of normal-hearing and hearing-impaired (HI) children. The simultaneous recording system employed consisted of acoustic recording, electroglotography (EGG), and a marker-based facial tracking device. Participants, aged between 9 and 12 years, included nine normal hearing children (4 females and 5 males) and six children with hearing impairments (3 females and 3 males). Participants were instructed to say the standard word list used for the Goldman-Fristoe Test of Articulation and a list of words including each of the vowels /i/, /a/, and /u/, preceded by the consonants /b/, /g/, or /s/ in a CV, CVC or CVCV context. In total, the second word list included 45 words (3 vowels X 3 consonants X 5 trials) and participants were asked to repeat a second time using an open jaw posture. Measures of the acoustic signals included: frequencies of formants one and two (F1, F2), fundamental frequency (F0), percent jitter, percent shimmer, signal-to-noise ratio (SNR), vowel length, consonant length, and spectral moments (M1 and M2). Vowel spaces, derived from F1 and F2, were also analysed. The EGG measures included fundamental frequency, open quotient, and speed quotient. The marker-based facial tracking signals was analyzed to derive the measure of maximum jaw displacement. Individual participants' measures were submitted to a series of two-way Analysis of Variances (ANOVAs) and the average data for participants in the normal-hearing group to a series of two-way repeated measures ANOVAs. Results showed that increased jaw opening led to an increase in vowel area (as shown by the F1/F2 plots of the vowels /i/, /a/ and /u/). A significant decrease in SNR was also found for many participants in the open jaw condition, indicating increase vocal stability. The HI participants showed smaller vowel areas than their normal-hearing peers. These results suggest the utility of increase jaw opening may increase vowel area and voice quality for both HI and normal-hearing children.

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Chapter 1. Introduction

1.1 Thesis Overview

The negative impact of hearing impairment on speech production has been shown in a number of studies over the years (Hudgins & Numbers, 1942; Smith, 1975; Parkhurst & Levit, 1978; Boothroyd, 1984). Findings from an auditory analysis of speech errors in 192 pupils from two oral schools for the deaf or hard of hearing showed that the number of children's speech errors was proportional to their level of hearing impairment (Hudgins & Numbers, 1942). Various methods of speech training have been developed to improve hearing impaired (HI) children's speech production for better intelligibility. A common approach used in the speech training of HI children is for the clinician to model the production of speech sounds for the child (Ling, 1976). This natural modelling method has its limitations as many speech sounds are not easily distinguishable through visual observation of facial and articulatory movements. Therefore, spectrography has been used to provide visual cues for improving the place and manner of articulation (Ertmer, Stark & Karlin, 1996; Ertmer & Maki, 2000). Other instrumental techniques such as electropalatography (EPG) have been employed to provide more legible visual cues in tongue placement and other articulatory gestures (Gibbon, Stewart, Hardcastle, & Crampin, 1999). The acoustic monitoring technique, as compared with EPG, has the advantage of minimizing the physical interference to movements of speech articulators during speech production as well as providing a basis for bridging perception and production. When simultaneously recorded with other physiological signals, acoustic signals also allow for an investigation on the effect of a certain articulatory change on the speech and voice output. A better understanding of the acoustic-physical link in speech production will enhance the usefulness of employing a visual display of acoustic features as a biofeedback for speech training, especially for individuals whose auditory input has been compromised due to hearing impairment.

As vowels bear information on prosody and adjacent consonants and vowel identification are highly correlated with speech intelligibility (Monsen & Shaughnessy, 1978), it is generally agreed that vowel errors have a greater effect on speech intelligibility than consonants or suprasegmental features (Smith, 1975; Maanssen & Povel, 1985). Therefore, vowel production tends to be the primary focus of speech training for the hearing impaired (Ertmer et al., 1996; Monsen & Shaughnessy, 1978). In a study of vowels, Angelocci, Kop, & Holbrook (1967) found that male HI adolescents, as compared with normal controls, showed a more restricted vowel production area, resulting in inadequate distinction between vowels and, consequently, a reduction in intelligibility (Angelocci et al., 1967). As vowel production area may be facilitated through a greater jaw opening posture during speech, it appears that an open mouth approach is likely to increase the space of the oral cavity to allow for more distinct articulatory placements for different vowels. The exaggerated jaw opening technique, such as the "yawn-sigh" technique, has been applied in singing training (Boone & McFarlane, 1993) and in voice therapy for those with vocal hyperfunction (Boone, 1993). However, there is a lack of empirical evidence showing the effect of an open mouth approach on the speech and voice of HI children. To determine whether and how increased jaw opening may facilitate increased vowel production area and vocal stability in HI children as well as normal-hearing children, this study employs a multi-channel system to obtain simultaneous recordings of the acoustic and physiological signals during speech produced by normal-hearing and HI children.

1.2 Literature Review

This section starts from a critical review of theories of the acoustics of speech production, impact of hearing loss on language acquisition, and habilitation of prelingually deaf children, including the contribution of cochlear implants to habilitation and related speech problems and therapeutic approaches for HI children, and ends with a general discussion on the use of instrumental measures of speech and voice.

1.2.1 Acoustics of speech production

Speech production involves a complex physiological process, converting egressive airflow from the lungs into acoustic energy which is then modulated or released by the vocal folds and filtered in the vocal tract (Kent, 1997). In the production of consonant sounds, airflow passes through the vocal tract with different shapes and varying degrees of constriction resulting in "noise". Consonants are often classified by manner (i.e., the way air is released from the constriction in the vocal tract) and place of articulation (i.e., the place where the constriction is formed in the vocal tract). Consonants can be produced in conjunction with vocal fold vibration resulting in a voiced consonant, or with inactive (abducted) vocal folds, resulting in an unvoiced consonant (Ling, 1976). Voiced sounds, either voiced consonants or vowels, involve the quasi-periodic vibration of the vocal folds which determines the fundamental frequency (F0) or pitch of a sound (Lieberman & Blumstein, 1988). In vowel production, the vocal tract serves as a filter, whose resonance characteristics are determined by the position of the tongue as well as the configuration of the vocal tract. The F0 of voiced sounds remains relatively unaffected by the resonance characteristics of the vocal tract (Perkins & Kent, 1986). However, different frequencies of the source sound are accentuated by particular articulatory configurations, producing formants in voiced sounds (Fry, 1979). Formants are clusters of the harmonics of the F0 with the highest energy. Vowels can be differentiated auditorily based on the relative position of their formants, especially with regard to Formant one (F1) and Formant two (F2), which are the first and second highest, and leftmost peaks shown in the spectral envelope, respectively (Davenport & Hannahs, 1998). According to Perkins & Kent (1986), vowels can be classified by the tongue position along two dimensions: tongue height (which is closely related to F1), and front-backness of the tongue (which is related to F2). Since vocal tract length varies by the individual, the frequency at which the formants are present will depend on an individual's vocal tract length. For example, as children and women have shorter vocal tracts than the average male, the frequencies at which the formants resonate will be higher for children and women (Zemlin, 2007; Behrman, 2007).

1.2.2 Impact of Hearing Loss on Language Development

Children begin the process of acquiring language from birth, as they are exposed to the speech of those around them (Northern & Downs, 2002). In studying the level of the sucking of ten newborn infants in response to voice recordings of different females, DeCasper & Fiefer (1980) found that newborn infants could distinguish, and showed a preference for, their own mothers' voices. The "critical" period of learning a language, including developing the auditory skill for discriminating between phonemes in a language, is considered to be from zero to five years of age (Kirk & Hill-Brown, 1985; Carney & Moeller, 1998). Individuals who become deaf after the acquisition of language (i.e., postlingually deaf) are likely to have minimal speech problems. As postlingually deaf people have had a period of exposure to the sounds and patterns of their language, they have a mental representation of how their language sounds and how they can physically produce it. When a child is born with a hearing impairment or develops one soon after birth (i.e., prelingually deaf), he or she has less opportunity to overhear language. Depending on the severity of the hearing loss, prelingually deaf people are deprived of some, or all, of the acoustic information needed for the acquisition of language. Table 1 shows some characteristic speech problems associated with different levels of prelingual hearing loss.

Because a child with profound hearing loss receives much less of the acoustic information relayed in the speech stream than a child with a mild or moderate hearing loss, it is not surprising that the level of speech production problems has been found to be proportional to the level of hearing loss (Hudgins & Numbers, 1942; Boothroyd, 1984). While a child with a mild hearing loss may have few or no speech production problems, a child with a profound sensorineural loss may struggle to develop language, even with amplification (Kirk & Brown, 1985; Osberger, Maso, & Sam, 1993; Northern & Downs, 2002). As HI children's speech problems associated with their hearing impairment are likely to render them unintelligible to most other speakers, speech impairment may lead to communication difficulties and even social isolation (Carney & Moeller, 1998).

Loss of auditory input has been found to have a negative impact on the speech production abilities of the HI population (Hidgins & Numbers, 1942; Smith, 1975; Eisenburg, 2007). Boothroyd (1984) for example, studied the speech perception and speech intelligibility of a group of 120 individuals (aged between 11 and 18) with varying degrees of prelingual hearing loss. As predicted, participants' performance on a forced-choice speech perception test was related to the severity of their hearing loss, with progressively higher hearing thresholds affecting the distinguishment of consonant place, consonant voicing, vowel place (front versus back), and vowel height (high versus low) respectively, and with intelligibility decreasing proportionally to the level of hearing loss. In a study of the average intelligibility of 40 deaf children, Smith (1973) found that the mean intelligibility of the deaf children's speech for unfamiliar listeners was as low as 18.7%. Smith (1973) also found that segmental errors were highly correlated with the level of intelligibility, especially for vowels and diphthongs. In other words, as segmental errors increased, intelligibility decreased. These findings showed that hearing loss had a negative impact on speech production and the extent of impact depended on the severity of prelingual hearing loss.

1.2.3 Habilitation of Hearing Impaired Children

The benefits of early identification and appropriate intervention for young children with hearing loss have come into play in recent years with the development of and improvement in hearing aid and cochlear implant technology. When a hearing loss is discovered at a young age, amplification or cochlear implantation can maximize the auditory stimulation which is needed for the child to acquire language during this critical period. While hearing aids amplify the sound pressure presented to the ear, cochlear implants convert acoustic sound energy into an electrical form which stimulates the auditory nerve directly, bypassing the damaged hair cells in the cochlear (Holmes, 2002).

1.2.3.1 Contribution of Cochlear Implant

Recent studies have generally shown that the speech production skills of profoundly deaf children using cochlear implants are better than comparable children using hearing aids. This could be attributed to increased access to auditory information (such as high frequency consonant sounds) through the implant via speech processing strategies (Uchanski & Geers, 2003). Van Lierde, Vinck, De Vel, & Dhooge (2005) compared the speech characteristics of 9 children with cochlear implants and 6 children who were using bilateral hearing aids. Objective and subjective methods of analysis were used to evaluate the children's overall intelligibility, articulation, phonation and resonance. It was found that children using cochlear implants were more intelligible than children who used hearing aids, with the hearing aid group exhibiting a higher level of phonological and phonetic disorders. Law & So (2006) studied 14 profoundly deaf children; seven with cochlear implants and seven who were using hearing aids. Each child had been identified by two years of age as having a hearing loss. The children were full-time users of their aids or implants and spent similar lengths of time participating in speech training. Participant's phonological abilities and processes were assessed through picture-naming and storytelling. It was found that the children using cochlear implants were able to develop better phonological abilities than those using hearing aids. Uchanski & Geers (2003) investigated the acoustic speech characteristics of 181 children with cochlear implants and 24 normally-hearing children. Objective acoustic measures, including measures of formant frequencies, spectral moments, nasality metric, and durations of vowels words and sentences, were taken from participants' speech samples, as they copied sentences produced by the experimenter. It was found that a large number of children using cochlear implants produced acoustic measures compatible with children with normal hearing. Evidence showing that children using implants produced better speech than those using hearing aids suggested that acoustic information (better captured through cochlear implants) was key to the acquisition of accurate speech..

The level of language attained by a prelingually deaf child using a cochlear implant is dependent on variables such as age at implantation (Ertmer, Young, & Nathani, 2007), type of rehabilitation method used (Osberger et al. 1993; Vieu et al., 1998; Bouchard, Normand, & Cohen, 2007), non-verbal intelligence, parental and child motivation to learn, and length of device use (Wie, Falkenberg, Tvete, & Tomblin, 2007). Outcomes are also affected by the device itself such as: how close the electrodes are to the nerve cells, whether there are dead regions where no cells can be stimulated, the sophistication of the technology, and type of speech processing strategy used (Homes, 2002). Despite these considerations, advances in the application of cochlear implants has generally increased the likelihood of developing adequate oral speech in the prelingually deaf and thus the importance of developing speech training with effective usage of auditory and visual feedback.

1.2.3.2 Speech Problems of the Hearing Impaired

This section discusses the speech characteristics in children with different levels of hearing loss, including mild to moderate and severe to profound HI children, and cochlear implanted children. Secondly, the vowel production, consonant production, supresegmental production, resonance and velopharangeal Control is discussed. Finally the speech characteristics of profoundly deaf children using cochlear implants from a young age is discussed.

1.2.3.2.1 Mild to Moderate Hearing Loss

Children with a mild to moderate hearing loss are likely to develop intelligible speech. Aided through early and appropriate amplification, children with a mild to moderate hearing loss are likely to be compatible with normal-hearing children in terms of articulation problems or phonological delays (Seyfried Culbertston & Kcricos, 2002). For children with mild to moderate hearing impairments, consonant phonemes, such as affricates, fricatives, and blends, are the speech sound most commonly misarticulated. Elfenbein, Hardin-Jones and Davis (1994) studied a group of 40 children with mild to moderate prelingual hearing loss. Participants, divided into three groups according to the severity of hearing loss, were administered a battery of tests assessing their speech and language. The Fisher-Longemann Test of Articulation Competence was used to assess the participants' speech. It was found that the most common consonant error was subsitution, followed by distortion, and omission of consonants. These errors were most likely to occur when producing fricative and affricate consonants. The authors concluded that the speech of children with mild to moderate hearing impairments is more similar to the speech of normal-hearing children than to the speech of the profoundly deaf (Elfenbein, Hardin-Jones & Davis, 1994). Children with mild to moderate hearing loss are likely to have less difficulty with vowel production than with consonant production because vowel sounds tend to be louder than consonants (Stevens, 2002), with mostly harmonic energy and with a higher concentration of energy in the lower frequencies (Van Lierde et al., 2005).

1.2.3.2.2 Severe to Profound Hearing Loss

The speech of children with profound hearing loss encompasses a greater range of speech errors than that of children with less severe hearing loss. This can be attributed to the greater deficiencies in the hearing threshold, further decreasing access to the frequencies most important for speech. Table 1 shows characteristic speech and voice errors of the hearing impaired as found by various investigators. The speech problems in children with profound hearing loss may be viewed from different aspects, including consonants and vowels, suprasegmetnal features, and resonance and velopharyngeal control.

Consonants and Vowels. Consonants are more likely to be misarticulated than vowels as they are generally softer, higher-pitched sounds (Law & So, 2006). Consonantal errors include substitution, final consonant deletion, consonant cluster distortion, and reduction. Voicing errors are also common; for example, consonants such as "s" and "z" may be used interchangeably (Dagenais & Critz-Crosby, 1991). Contrast of voicing is important because it distinguishes phonemes with the same place of articulation such as /p/ and /b/. As there is not a readily visible articulatory difference between voiced and voiceless cognates, prelingually deaf people may have difficulties making adequate differentiation between them. Intrusive voicing can also be a problem. In such a case, voicing precedes the burst release of the plosive, making a /b/ sound similar to /m/ (Ling, 1976). As for vowels, results of a study of the speech characteristics of 120 deaf adolescents (aged between 14 and 20 years) revealed that vowels tended to be substituted, distorted, neutralized, diphthongized, or nasalized in this population (Hudgins & Numbers, 1942).

Suprasegmental Features. Suprasegmental features of speech, such as stress, pitch, and intonation, are also often incorrectly used resulting in reduced speech intelligibility. In English, as well as other non-tonal languages, the position of stress in a word can change the associated meaning. Speakers with a profound hearing loss may attempt to compensate for their inability to distinguish stress patterns by producing equal stress on each syllable. Intelligibility is hindered rather than helped by this (Maassen & Povel, 1985). Borg, Edquist, Reinholdson, & McAllister (2007) studied a large group of 4 to 6 year old Swedish-speaking children with normal hearing, to severe hearing losses. In the study, 156 subjects had hearing loss while 97 had normal hearing. Testing covered a wide range of perceptual and productive language abilities. It was shown that the more severe a child's hearing loss, the more difficult it was for them to correctly produce word stress, particularly word final stress (in Swedish word initial stress is more common). Children with a 61 to 80 dB HL hearing loss produced only at a level of 61% correct for initial word stress and 31% correct for final word stress. In contrast, the averages of percent correct for production of initial and final word stress were 84% and 59% for children with a 21-60dB loss and 91% and 74% for normal-hearing children (Borg et al., 2007). In the profoundly deaf pitch has been found to be elevated in comparison with normal-hearing speakers (Maassen & Povel, 1985). Maassen & Povel (1985) examined the effect of correcting suprasegmental features of sentences spoken by deaf children on the inteligibility. Sentences before and after correction were played to six groups of 16 to 20 listeners to get an overall intelligibility rating. It was found that intelligibility only increased from 24%, without correction, to 37%, with corrected suprasegmental features. It appears that despite the monotonous quality exhibited in deaf speaker's speech, elevated F0 is unlikely to impact on the overall intelligibility.

Resonance and Velopharangeal Control. Hypernasality or the presence of nasal resonance in oral sounds, is a problem which is not uncommon for the HI (Hudgins & Numbers, 1942). Nasalized vowels are produced through the coupling of the naso-pharynx to the vocal tract by lowering the velum, resulting in the presence of different resonances and anti-resonances in the vowel spectrum (Ohala & Ohala, 1993). Research has shown that HI children may have difficulty with velopharangeal control, resulting in the perceived nasality of their speech (House & Stevens, 1956; Stevens, Nickerson, Boothroyd, & Rollins, 1976; Ysunza, 1993). Disordered timing and positioning of the velum can lead to inappropriate nasal coupling for oral sounds. Lack of auditory feedback, with which to maintain the distinction, is the most likely cause (Ysunza & Vazquez, 1993). In purely oral sounds, speech energy is radiated through the oral cavity with a raised velum. For purely nasal sounds, the velum is completely lowered and the energy is radiated through the nasal cavity. When the velum is partially lowered, energy can radiate through both cavities. As greater dampening of the radiated spectrum may occur in the nasal tract than in the vocal tract, velum lowering may lead to a nasal quality in the vowel. In addition, since the nose, due to the smaller size, may provide less sound energy than the mouth (Ohala & Ohala, 1993), velum lowering may lead to reduced loudness of the vowel.

1.2.3.2.3 Cochlear Implant Users

The language outcomes of children using cochlear implants are highly variable due to the large number of variables involved, as discussed above. However, there is increasing evidence suggesting that children using cochlear implants may successfully develop language. Ertmer (2001) sudied the emergence of vowels of a young girl during the first year following her implantation at 19 months. Before implantation she produced three types of vowel. After one year of using a cochlear implant she could produce 9 vowels with a near normal "vowel space", which is a F1-F2 plot of vowels representing the acoustic area of the vowels produced by an individual (Neel, 2008). Bouchard et al. (2007) studied 20 children who were using cochlear implants. They found that after 18 months of auditory experience using a cochlear implant, the children produced plosive and labial consonants more frequently than glides and palatal consonants, the use of which remained infrequent. They found that initially, the most visible consonants were acquired, but as experience using the auditory information was gained, speech development closely resembled that of normal-hearing children. Van Lierde et al.

(2005) studied 9 children with cochlear implants and 5 children who were using hearing aids. Speech characteristics of each group were analysed using subjective and objective measures. Normal vocal quality and resonance was found for the speech of the cochlear implant group. Some distortions and phonological disorders were present and some fricative sounds were absent. Overall, the children using the cochlear implants had fewer phonological problems than the hearing aid group. In a study by Law & So (2006), a higher proportion of children could accurately use more visible phonemes, such as those in the anterior portion of the mouth, than phonemes further back in the mouth such as the velar /k/. Consonants contained more errors than vowels, with fricatives /f, s/ and affricates /ts, ts^h / being released as plosives. The bilabial approximant /w/ in /k^w/ and /k^{wh}/ became delabalised. They concluded that these error patterns are used by normal-hearing children as they acquire the Cantonese language.

Lenden & Flipsen (2007) carried out a longitudinal study investigating the prosody and voice characteristics of 6 children fitted with cochlear implants before age 3. For these children, pitch and phrasing were not significant problems, as they are for children with severe to profound hearing loss. However, stress and resonance were still problematic. Problems with rate and loudness were also present but only in a small subset of the speech samples. The findings from this study suggest that children using cochlear implants have less of a problem with prosody and voice characteristics than those with comparable hearing impairments using hearing aids. However, Tomblin, Spencer, & Hurtig (2007) studied the interrogative responses of 24 prelingually deaf children with cochlear implants and found that the children were not able to imitate rising intonation appropriately. Although some improvement in the producton of prosody has been shown with increase in device experience, implants remain inadequate in coding for prosody and pitch information, leading to limitations in children's understanding and production of these areas of speech.

1.2.3.3 Speech Therapy for HI Children

Hearing loss may affect a child's language and speech development as well as their academic and social development. Literacy, family dynamics, and employment opportunities can be disrupted. Maximizing the speech intelligibility of deaf children helps integrate them into the hearing world as well as the deaf world (Crawford, 1995). Speech problems associated with hearing impairment are generally managed through speech and language therapy. In particular, it is useful to improve hearing impaired children's pronunciation of vowels, as the overall intelligibility of speech is most affected by vowel accuracy (Smith, 1975), and consonants may be deduced from the vowels which they surround (Monsen & Shaughnessy, 1978). Two approaches, based on theories of the way we perceive and reproduce sound, have been applied to speech training: the motor-based approach and the perceptually-based approach.

1.2.3.3.1 Perceptually-Based Therapy

Based on the acoustic theory of speech production, perceptuallybased therapy posits that speech production is guided by an internal map which has been formulated through our perception and discrimination of the sounds. The input of the speech signal is divided into acoustic segments, giving us an internal map of speech sounds (Stevens, 2002). Hearing impaired people are not able to perceive the same phonetic differences and thus they form a deviant internal phonetic map resulting in incorrect speech production. Perceptually-based therapy utilises objective feedback which aims to compensate for the lack of auditory access to acoustic patterns of speech sound. Methods of objective visual feedback include spectrographic displays (Ertmer et al., 1996; Ertmer & Maki, 2000), EPG (Crawford, 1995; Gibbon et al., 1999), and pneumotachography (Mashie, Vari-Alquist, Waddy-Smith, & Bernstein, 1988).

Spectrographic display can be used as a means of 'visual feedback' in the speech training of hearing impaired individuals. Someone using this training method is able to see the visual representation of their speech in real time. This removes the time delay between the production of a deviant speech sound and the correct modelling by the speech therapist. For the spectrographic display training, two windows are shown on a computer screen. One shows the correct production of a target and the other shows the subject's production (Ertmer & Maki, 2000). Ertmer et al. (1996) used real-time spectrographic displays in the vowel production training of two nine-year-old children with profound hearing loss. The children participated in half hour training sessions, three days per week for five months. This involved familiarization with spectrographic displays, instruction and feedback on correct tongue placement, and self-evaluative vowel production practice. Significant and maintained improvement was shown in all the target vowels (/i/, /o/, /a/ and /æ/) by the first child, following training. The second child only maintained significant improvement in the target vowel /a/. The authors concluded that the second child needed more intensive training than the first and speculated that further training would have shown improvement in the production of all the target vowels.

Another way of providing visual biofeedback is EPG, which consists of sensors embedded in an acrylic pallet placed over a person's hard palate in the mouth (Seyfried et al., 2002). These sensors create an electrical circuit when the tongue meets the pallet, providing precise timing and placement information shown on a computer screen. Gibbon et al. (1999) describe the case of an 8-year-old boy who did not show improvement after participating in 33 conventional speech treatments in an attempt to correct his production of /t/, /d/, /tʃ/and /dʒ/. After undergoing 32 half-hour treatment sessions using EPG over a six- month period however, the boy could produce perceptually normal alveolar plosives and affricates, demonstrating the usefulness of the visual biofeedback.

Pneumotachography, which consists of an airflow transducer (with pressure sensors) and a mask which can be placed over the mouth and nose, can be used with a computer display to provide visual information on changes of the airflow rate level during phonation (Rothenberg, 1977). Mashie et al. (1988) conducted a subjective study which looked at the effectiveness of two computer-based training programmes which utilise acoustic and physiological measures to provide visual feedback in the facilitation of speech development of children. Fifteen hearing impaired children, aged three to eleven, took part in clinic-based and home-based training, in an interactive computer game format. Pneumotachography was used to give visual information on airflow during clinic-based sessions. Based on subjective feedback, provided by the two clinicians who conducted the training, it was reported that use of the acoustic and physiologic visual feedback enabled the child and the clinician to gauge correct articulation, limiting mistaken reinforcement of incorrect productions by the clinician. Mashie et al. (1988) also commented that the visual biofeedback using pneumotachography might facilitate the motivation level of children to be engaged in speech training. To date however, while some studies have demonstrated some success in employing various visual biofeedback techniques for improving speech production, more traditional methods are more likely to be administered in an everyday clinical situation.

1.2.3.3.2 Motor-based Therapy

The traditional approach to improving the speech articulation of deaf children is motor-based. Motor-based therapy claims that improving the physical articulation of a speech sound will correct the perception of that sound, as all speech sounds are represented as motor commands in the brain (Liberman et al., 1967). This involves the maximization of residual hearing through amplification, modelling of speech sounds by the clinician, visual cues and tactile cues (Ling, 1976; Seyfried et al., 2002). This therapeutic approach is based on Liberman, Cooper, Shankweiler, & Studdart-Kennedy’s (1967) motor theory of speech perception. Speech sounds produced in visible areas of the mouth, such as anterior consonants, are easier to learn than sounds which are produced further back in the mouth, which visually do not distinguish themselves. Coronal consonants and vowels which are not distinguishable through lip spreading or lip rounding are difficult to learn through visual cues and modelling. In these cases the child relies on the subjective feedback from the clinician to determine if they are producing a sound correctly (Dagenais, Critz-Crozby, Fletcher, & McCutcheon, 1994; Ertmer et al., 1996).

1.2.4 Open Mouth Approach

Training methods involving increased opening of the mouth (motor-based therapy) have been used in singing training and speech and voice therapy in order to relax the vocal tract and to increase clarity of articulation (Cookman & Verdolini, 1999; Shrivastav, Yamaguchi & Andrews, 2000; Freed, 2000). Since reduced jaw movement gives less room for distinct tongue positions in the articulation of vowels, greater space in the oral cavity is considered to be more likely to provide defined vowel areas, which may increase intelligibility. Increased jaw opening has been shown to increase laryngeal adduction (closing) at conversational pitch giving greater vocal stability (Cookman & Verdolini, 1999). Lindblom and Sundberg (1971) used x-ray tracings to examine the acoustical effects of jaw opening, lip spreading, and tongue and larynx height on different vowels produced by one Swedish-speaking participant without pathology. A shift in the first three formants in frequency were observed with increased jaw opening, indicating that jaw manipulation can alter the acoustic properties of vowels (Lindblom and Sundberg, 1971).

One speech facilitation technique involving increased jaw opening is overarticulation training. This consists of "Purposeful, exaggerated articulation of consonant phonemes" (Freed, 2000 p. 319). Intelligibility may be indirectly improved as speakers may attempt to articulate more precisely and speak more slowly (Searl & Carpenter, 2002). Boone (1993) suggests that oral openness (or opening the mouth more during articulation) aids vocal hyperfunction, pitch, loudness and quality of voice causing one to use the "vocal mechanisms more optimally." (p162). Forms of 'open jaw posture' are used in traditional speech and singing training (Cookman & Verdolini, 1999) such as the 'yawn-sigh' technique (Boone & McFarlane, 1993). The yawn sigh technque is a yawn followed by a sigh used to relax the vocal tract and decrease vocal hyperfunction. Boone & McFarlane (1993) studied the vocal characteristics of eight normal adult subjects while performing the yawn-sigh technique using video nasoendoscopy. They found that the subjects who were able to perform the technique had a lowering of the larynx and a widening of the pharynx producing a relaxed vocal tract. Shrivastav et al. (2000) compared different vocal simulation techniques (including the yawn-sigh technique) commonly used to relax the larynx. Eleven female singing students, without vocal disorders, were recorded acoustically and with a videoendoscope phonating the vowel /a/ using different stimulation techniques. Consistent with Boone & McFarlane (1993), endoscopic examination showed a lowered larynx following the yawn-sigh technique. However, acoustic analysis showed a raised fundamental frequency, consistent with an increase in tension in the larynx. Cookman & Verdolini (1999) studied twelve normal adults to look at the effects of jaw opening and jaw biting on laryngeal adduction. Electroglottography was used to measure the amount of vocal fold closure. It was found that, at least for normal conversational pitch, increasing jaw opening resulted in increased laryngeal adduction.

Ling (1976) suggests that hearing impaired children may use the jaw excessively, with minimal tongue movement, in order to distinguish vowels. While excessive jaw movement is not intrinsically linked to hearing impairment, the use of exaggerated modelling of sounds, which are normally visually indistinguishable, in speech training, can lead to inappropriate overarticulation (Ling, 1976). While open jaw or open mouth posture is a common technique to improve intelligibility for those with vocal disorders or as an aid for singers, there is a lack of objective assessment and treatment efficacy studies. Although there is some evidence that a more open mouth approach can improve articulation and voice quality, giving clearer vowel articulation, modelling with an exaggerated open mouth may be maladaptive for a hearing impaired child who has not learned the defined articulatory tongue positions for different vowels. Further evidence is needed to assess whether the open mouth approach is beneficial for use with hearing impaired children.

1.2.5 Instrumental Measures of Speech and Voice

In order to assess the effectiveness of a treatment on speech production, a method of identification and discrimination is needed. Features of speech and voice production, for the purposes of identification and training, are generally indentified auditorily. In other words, they are based on the subjective, perceptual assessment conducted by a trained listener. Alternatively, studies have shown the utility of acoustic, instrumental methods to identify and study speech production errors. Some such methods are outlined in table 2. Using objective methods can give unbiased measures with which to identify various speech features. The following section outlines the use of acoustic analysis including: the spectrographic representation of consonants and vowels and the measurement of formants, voice onset time, spectral moment analysis, resonance, and voice quality. It then outlines the use of electroglotography and facial tracking.

1.2.5.1 Acoustic Measures

Spectrographic display provides a visual representation of speech sounds, with individual speech sounds showing characteristic patterns according to how and where they are produced in the mouth (Davenport & Hannahs, 1998). It is useful in the objective analysis of speech as rapid articulatory transitions and subtle changes in formant frequency can be analyzed

(Lieberman & Blumstein, 1988). The acoustic information shown on the spectrogram is beyond that which even highly trained phoneticians could provide.

1.2.5.1.1 Spectral Characteristics of Consonants and Vowels

On a spectrogram consonants can be primarily distinguished by their manner of articulation, although some features of their place of articulation are evident through the transitions between consonants and vowels. Table 3 shows the spectrographic representation of consonants by manner of articulation. Consonants can be divided into obstruent and sonorant consonants according to the way the airflow is produced through the vocal tract. Obstruent consonants are produced with airflow released through a restricted passage due to the close approximation or a complete closure of the articulators (Davenport & Hannahs, 1998). Obstruents can be divided into fricatives, plosives and affricates. Fricatives, which contain much high frequency noise, can be recognized on the spectrogram as high frequency, aperiodic energy. Plosives have an absence of spectral energy (during the closure of the articulators) and a stripe of energy as it is released, followed by weaker aspiration noise (Perkins & Kent, 1986). Affricates can be recognized as a plosive followed by a fricative with the same place of articulation (Behrman, 2007). Obstruent consonants can be produced with or without voicing. Voicing is present when a low frequency bar of energy is evident on the spectrogram. Sonorant consonats are produced without a restricted airflow through the vocal tract. These include nasals, liquids and semivowels or glides (Davenport & Hannas, 1998). They are simular to vowels in that they are only produced as voiced sounds in English and therefore give characteristic formant patterns. Nasal consonants can be recognised as low frequency bands of energy at approximatly 250 Hz, a ‘pole’ or absence of energy near

1 kHz for the higher formants. Glides and liquids can be recognised by the transition of their formants (Kent, 1997). For example, /r/ can be recognised by a noticeable dip in the third formant.

The place of articulation is revealed by more subtle features on the spectrogram. Aperiodic spectral 'noise', associated with the fricatives, becomes higher as the place of articulation moves anteriorly. For plosive consonats, especially those with voicing, the place of articulation can be indicated through the formant transitions of the previous or following vowel. For example, labial plosives /p/ and /b/ produce a raised F2 on the adjacent vowels, velar plosives will produce a divergent effect of F2 and F3 of the adjacent vowel and alveolar plosives will produce lowered F2 on the adjacent vowel (Davenport & Hannahs, 1998).

Many studies have shown that vowels are distinguishable by the relative positions of F1 and F2 on the spectrogram. Table 4 describes the relative position of formants of vowels across the dimensions of hight and frontness on the spectrogram. Formants appear as dark horizontal stripes along the length of the vowel with higher formants appearing higher up the spectrogram. The frequency of F1 and F2 can be measured to calculate vowel area, which is a visual representation of the articulatory distance between vowels. Deaf speakers have greater variability in formant measures resulting in more overlapping vowel spaces than their normal-hearing peers (Angelocci et al., 1967). Vowel production area has been linked with speech intelligibility, with a greater area associated with better intelligibility (Angelocci et al., 1967; Turner, Tjaden & Weismer, 1995). Smiljaniæ & Bradlow (2005) studied the effects of a technique called "clear speech" in Croatian and English. "Clear speech" is adopted by people when they wish to make themselves more intelligible to a listener who may have difficulty understanding them, such as someone with a hearing impairment. It involves deliberately speaking slowly, loudly and with an exaggerated articulation in an attempt to convey the message more clearly. In Smiljaniæ & Bradlow's (2005) study, sentences were recorded, of native speakers of each language, in a conversational and a clear speaking style. To yield an intelligibility rating for each speaker, these sentences, with the appropriate language, were played in noise, to twenty Croatian and thirty English listeners. The results showed that for both languages, the clear speech condition had a decrease in speaking rate and an increase in vowel area and F0. Overall, the intelligibility scores for both languages were greater in the clear speech condition than in the conversational condition.

A vowel-area plot can be useful to show differences in vowel space before and after training programmes (Monsen & Shaughnessy, 1978). Turner et al. (1995) studied nine adults with amyotrophic lateral sclerosis (ALS) to determine whether there was a relationship between speaking rate, vowel area, and intelligibility. The formant frequencies for four vowels produced at different speaking rates were measured. It was found that speech intelligibility increased with vowel area for both fast and slow speaking conditions. Monsen & Shaughnessy (1978) used a method of visual training to improve the vowel production of three children with profound hearing loss. Training took place for one hour per week over five months. A model of the mouth and diagram of the vocal tract was used to instruct the children on the correct tongue placement when articulating five vowels. Children with profound hearing loss were required to practice making a difference in articulation between similar vowels. Following training, spectrographic analysis showed an increased range in the first and second formants, indicating an improvement in vowel articulation. Less overlap between vowel frequencies indicated an expansion in the children's 'vowel space' giving more distinction between vowels.

1.2.5.1.2 Voice Onset Time

Another useful acoustic measure of speech which can be taken from spectrographic analysis is voice onset time (VOT). Voice onset time is defined as the time between the release of the plosive-burst and the onset of voicing (Uchanski & Geers, 2003; Liberman & Blumsein, 1988; Zemlin, 1998). Measurement of the voice onset times of hearing-impaired children's speech may provide information on their perception of voicing contrasts. Voice onset time creates an important perceptual distinction between voiced and voiceless cognates (Lisker & Abramson, 1964). According to Stevens and Klatt (1974), plosives are perceived as voiceless if VOT is above approximately 25ms and voiced if VOT falls below about 20 ms. Voice onset time differ in length according to place of articulation (ling 1976) with velar stops having the longest VOT (Zemlin, 1998). Hearing-impaired speakers often have difficulty maintaining the VOT distinction (Lane & Perkell, 2005). This has been correlated with reduced intelligibility of hearing-impaired speakers. Metz et al. (1985) studied the speech intelligibility and acoustic features of 20 students with profound hearing loss. Participant's speech was recorded for acoustic analysis and perceptual listener ratings of intelligibility. It was found that VOT for cognate pairs were predictive of speech intelligibility.

1.2.5.1.3 Spectral Moment Analysis

Spectral moment analysis is another objective measurement of speech sounds which is useful in the analysis of consonants. Based on a fast Fourier transform, it looks at the energy distribution at a point in time, analyzing the average, the variance, the skewdness and the kurtosis (peakedness) of the spectrum (Forrest, Weismer, Hodge, Dinnsen, & Elbert, 1990). It can reveal the spectral properties of consonants produced by normal speakers as compared with speech disorders (Tjaden & Turner, 1997) . Forrest et al. (1990) investigated whether spectral moment analysis could distinguish /t/ from /k/ in normal speaking children and if this difference could be shown in children with disordered speech who subjectively did not produce a contrast. They found there was more variablity in the acoustic measures obtained from the disordered speaking children than from the normally speaking children. One of the children produced an acoustic distinction between /t/ and /k/ even though this distinction was not perceptually evident. The authors concluded that this underlying distinction may indicate positive outcomes for treatment of the articulatory contrast. The information through spectral moment analysis may provide precise information into the nature of hearing-impaired children's consonant production deficits which can facilitate appropriate training for such errors.

1.2.5.1.4 Resonance

Nasalized vowels are produced through the coupling of the naso-pharynx to the vocal tract by manipulating the velum, resulting in the presence of different resonances and anti-resonances in the vowel spectrum (Ohala & Ohala, 1993). As discussed above, hearing-impaired children may have difficulty with velopharangeal control resulting in the perceived nasality of their speech. Nasal 'colouring' is represented in the vowel spectrum as an overall reduction of amplitude, especially of the first formant. Formants bandwidths are increased with an upward shift in centre frequency. Other effects which may be present are irregularities in upper formants, the presence of 'anti-formants' (or negative poles) and the elimination of third formants. High vowels tend to be perceived as more nasal than low vowels. This means that with some nasal coupling, /i/ will be more affected than /a/ (House & Stevens, 1956). Measuring vowel nasalisation is complicated because of subject differences, velar coupling area, vowel identity, and phonetic context. Most languages have at least some nasalized vowels. Co-articulation between consonants is common and may be the only information which indicates the presence of a nasal consonant (Chen, Slifka, & Stevens, 2007).

There are several ways to objectively measure the presence of nasality for research purposes with different degrees of invasiveness. One such measure is to use a nasometer or pneumotachometer which measures nasal air flow during phonation. A larger nasal airflow suggests more nasal coupling during phonation and therefore more nasality (Higgins, McCleary, Carney, & Schult, 2003). An accelerometer which is attached to the nose during phonation is another way to measure nasality. It gives the output of nasal vibrations which can then be analysed (Stevens, Nickerson, Boothroyd, & Rollins, 1976; Krakow & Huffman, 1993). Spectral analysis can also be used in the measurement of nasality. The advantages in using this method are that it is straightforward to measure as it is non-invasive. However, there are difficulties finding a single, reliable measure of nasality, as there are many factors affecting the spectra such as subject differences, velar coupling area, vowel identity, and phonetic context (Chen et al., 2007). In general, researchers have looked at the effect of the extra resonances and anti-resonances on the pattern of energy distribution in the spectrum (Krakow & Huffman, 1993). Chen, et al., (2007) studied the variability of nasality in different contexts in American English. They used a measure of the difference in amplitude of the first formant and the amplitude of the nasal pole near 1 kHz (AP-P1) to assess nasality in the selected words as A1-AP in nasal contexts is decreased. They found that in American English, nasalisation can occur with nasals in prevocalic and post-vocalic positions, and that a nasal-vowel-nasal context doesnot give more nasalisation than a vowel contest with one adjacent nasal (Chen et al., 2007).

1.2.5.1.5 Voice Quality

Perturbation measures can be used to assess the regularity of frequency and intensity of f0 during phonation, or stability of the vocal folds. Measures can be taken through the use of electroglottography (discussed below) or through acoustic measures. Excessive perturbation can be perceived as harshness or roughness of the voice (Perkins & Kent, 1986). This can be a problem for hearing-impaired speakers (Arends, Povel, Van Os, & Speth, 1990; Bolfan-Stosic & Simunjak, 2007). ‘Jitter’ is the cycle-to-cycle frequency variation of vocal fold vibration and ‘shimmer’ is the cycle-to-cycle amplitude variation of vocal fold vibration. Signal-to-noise ratio (SNR), another measure taken, is the energy ratio between the noise components and the periodic components (Milenkovic, 1987). Measures of jitter, shimmer, and SNR are taken during short-term steady state phonation, such as during a portion of a vowel. For normal voices, low level perturbation measures may be present (Horii, 1979), while disordered voices may have increased levels (Milenkovic, 1987). Gelfer (1995) studied the effects of F0, vowel, and intensity on measures of jitter, shimmer, and signal-to-noise ratio in 29 female participants with normal voice. A 1500 ms midportion segment obtained from the vowels /i/ and /a/ produced at different intensities and frequencies was analyzed using the CSpeech acoustic analysis programme. It was found that measures of jitter and shimmer were affected by F0 and intensity, with higher measures being associated with low frequency and low intensity vocalizations. Shimmer was also found to vary by vowel, with /i/ yielding lower shimmer measures than /a/ (Gelfer, 1995).

1.2.5.2 Electroglottography

Electroglottography (EGG) is a non-invasive technique used to monitor changes of vocal fold contact during vibration (Jaeger, Frohlich, Ackermann, & Schonle, 2001; Jiang, Lin, & Hanson, 2000; Chernobelsky, 2002). To measure EGG, two electrodes are placed on either side of the neck over the thyroid cartilage. A low voltage, high frequency electrical current is passed through the electrodes, creating a change in resistance as the vocal folds vibrate. The waveform obtained reflects the level of contact of the vocal folds during vibration. The point of greatest amplitude of the waveform corresponds to maximal contact of the vocal folds due to decreased resistance. This allows the electrical signal to pass easily. The lowest amplitude of the waveform corresponds to the maximally open point of the vocal folds due to an increase in resistance, preventing the current from passing as easily. EGG analysis (sometimes called a laryngograph) measures time ratios between phases of vocal fold vibration. Measures include F0, open quotient (OQ), which is the ratio of open phase to the cycle period, and speed quotient (SQ), which is the ratio of opening phase to the closing phase.

There are a number of studies which utilise this method of analysis in the adult population with and without vocal disorders (Higgins, Netsell, & Schulte, 1998; Jiang, Lin, & Hanson, 2000; Jaeger, Frohlich, Ackermann, & Schonle, 2001; Chernobelsky, 2002; Laukkanen, Leppänen, Tyrmi, & Vilkman, 2005). However, there is limited research which uses EGG to look at the vocal characteristics of children. One study which looks at the effect of singing education on vocal characteristics was conducted by Dejonckere, Wieneke, Bloemenkamp, & Lebacq (1995) studied 38 children, aged between 7 and 12 years, who received vocal training, and 43 who had received no vocal training. They were were recorded using a laryngograph while phonating the vowel /a/ at three different sound pressure levels. Measures of fundamental frequency, jitter and shimmer were derived. They found that the loudness of the phonation increased, and with an increase in age, perterbation of F0 decreased. Also, more vocal stability was demonstrated in the trained group than the untrained group. Another study involving a pediatric population by Cheyne, Nuss, & Hillman (1999) aimed to establish normative EGG data for children's voices. 164 girls and 85 boys aged between 3 and 16 years of age were recorded using a laryngograph while phonating the vowel /a/. Mean values for F0, jitter, open quotient and closed quotient were obtained. No age effect or gender effect was found. This study provides normative EGG data for the vocal characteristics of children. Arends et al. (1990) used EGG to study predictive value of glottal characteristics and the perceptual evaluation of vocal quality of twenty prelingually deaf children and five normal-hearing children aged between five and nineteen. Participants were recorded phonating the vowels /i/, /a/ and /u/ at three different loudness levels. Measures such as f0, jitter, shimmer and closed quotent were taken from the waveform and correlated with listener-rated measures of voice quality. Jitter was the measure which had the most predictive value for ratings of voice quality. Other measures showed less predictive value. Linders, Massa, Boersmaa & Dejonckereb (1995) used EGG to investigate the effect of age and height on the F0 and jitter of

71 children aged 7 to 15 years. Fundamental frequency was measured using a laryngograph (with EGG electrodes place at the larynx) and EGG analysis software. It was found that F0 decreased with height and age, however there was no significant gender effect.

1.2.5.3 Facial Tracking

Jaw and lip displacement have been studied using methods which track the level of movement during speech. Tye-Murray & Folkins (1990) used a strain gauge system to measure the jaw displacement of 3 hearing-impaired and 3 normal-hearing adult speakers to investigate whether known stress patterns could be correctly produced by the normal-hearing speakers. Oscillographic records produced were digitized and analyzed. Results showed that deaf speakers as well as hearing speakers could produce different jaw displacements and durations according to the appropriate stress pattern. Tye-Murray (1991) used a microbeam apparatus to obtain measures of tongue and jaw displacements of three deaf and two hearing adults. Gold pallets, placed on the lower lip and tongue, were used to track tongue trajectories during articulation. Results showed that, similar to normal hearing subjects, HI participants displaced their tongue bodies during opening gestures. However, vowel trajectories were similar for all vowel contexts. Green, Moore, & Reilly (2002) used a jaw-tracking device to study the vertical lip and jaw movements of children and adults. They used a camera to track the movements of three reflective dots placed on subjects' lips and jaw, compared to reference dots on the subject's nose and forehead. These dots were illuminated with infared light. Movements were extracted using Motus, version 2, Peak Performance movement tracking software, and analysed using a near-zero crossing of the extracted velocity of the trace. They found that the children's jaw movements were closer to the adult form, compared to their lip movements, which had more variability. Walsh & Smith (2002) looked at the development of lip and jaw motor-control for adolescents, compared to young adults. They used Northern Digital OPTOTRAK

3020 three-camera system to record three-dimensional movements from infrared light-reflecting diodes attached to participant's lips and jaws. They found that the trajectories for lip movement were less variable than for jaw movement, however the results did not suggest that jaw movement is developed before lip movement. Adolecents showed greater variability than adults in the measures used.

1.3 Research Outline

Based on the findings, as outlined above, concerning the utility of objective measures of speech and voice and the possible benefit of open jaw posture, this study uses a simultaneous recording technique to investigate the use of open jaw posture in children with and without hearing impairment. The following sections outline the aims and hypotheses of the present study.

1.3.1 Statement of the Problem

Previous research has shown the utility of objective measures in the analysis of speech for adults and children with speech problems and with hearing impairment (Tyrmi, & Vilkman, 2005; Dejonckere et al., 1995; Forrest et al., 1990; Monsen & Shaughnessy, 1978). However, few studies incorporate the use of similtaneous recording with mulitiple objective measures such as acoustic, EGG and facial tracking analysis. Some studies have looked at the effect of exaggerated open jaw techniques on vocal stability in adolescents and adults with normal hearing (Boone & McFarlane 1993; Shrivastav et al., 2000), however, evidence is lacking as to the effects for HI children. This leads to questions such as: does open jaw posture increase the vowel area and vocal stability of children with hearing impairment?;and what are the main differences between HI and normal-hearing children's speech and voice characteristics when using this technique?

1.3.2 Aims of Study

In light of the lack of evidence showing the usefulness of an open mouth approach in improving the speech and voice of HI children, this study aimed to obtain acoustic and physiological measures to assess the facilitative effect of an open jaw posture on this population. In particular, objective measures of articulation, voice quality, and jaw movement were obtained to gain further insight into the speech characteristics of both HI children and children with normal hearing, while speaking normally and when using an open mouth approach. A simultaneous recording technique, consisting of acoustic, EGG and facial tracking recordings, was employed. The benefit of this system is that while providing a number of different informative measures, a comparison between some acoustic measures and physiological measures (EGG and facial tracking) could be made to increase the accuracy and consistency of analysis. Findings from this study will add to the current body of literature regarding the open mouth approach and the speech and voice of children, with and without hearing loss, using instrumental measures.

1.3.2 Hypotheses

It was hypothesised that open jaw posture would (1) facilitate movements in F1 and F2 in a way that resulted in an increase in the area of vowel space for both normally-hearing and HI participants, (2) increase vocal stability as could be measured by a decrease in perturbation measures and an increase in signal-to-noise ratio. Most importantly, it was hypothesized that HI children would have more restricted vowel areas than their normally-hearing peers during normal articulation and thus would show more improvement in speech and voice production with an open jaw posture. A consonant context effect on the speech and voice measures was also expected.

Chapter 2. Method

2.1 Participants

A group of normal-hearing and a group of HI participants were recruited from the Christchurch area using a convenience sampling method. Subject inclusion criteria for the normal-hearing group were: English as their first language; aged between seven and twelve years; normal hearing, and no history of speech and articulation problems. Subject inclusion criteria for the HI participants were: English as their first language; aged between seven and twelve years; moderate to severe prelingual hearing impairment, and using oral communication. For both groups, subject exclusion criteria were: signs of behavioural or learning problems or neurological or other health conditions. To recruit normal-hearing children, verbal and written invitations were given to parents with normal-hearing children living in the Canterbury area. To recruit HI children, letters were sent via the Advisors of Deaf Children (AODC) to parents of HI children living in the Canterbury area. The AODC are a governing body of professionals who provide support and advice to hearing impaired children and their caregivers in a community setting.

The normal-hearing group consisted of five males and four females, aged between 9 and 12 years (see Appendix 1), with a mean of 10.8 years (SD = 1.2). The HI participants included three females and three males, aged between 7 and 12 years (see Appendix 2), with a mean of 10.2 years (SD = 1.9). All participants had normal voices and were monolingual native speakers of New Zealand English except for one HI participant who was a bilingual speaker of New Zealand English and German.

2.2 Materials

The test materials used in this study were the Goldman-Fristoe test of articulation and a specifically tailored word list. The Goldman-Fristoe test consists of a standard word list which covers all 23 English consonant phonemes. The word list created for this study included CV (consonant-vowel) words with each of the three consonants /s/, /b/, and /g/ followed by one of the three corner vowels /i/, /a/ and /u/. Where an open CV word using the selected consonant and vowel was not available, a closed syllable (CVC) word with the target consonant on the initial position was used. Where a CVC word using the selected combination was also nonexistent, a two-syllable CVCV word with the stress on the first syllable was used. As a result, the word list employed 4 different CV words, 4 different CVC words, and 1 different CVCV word. The vowels /i/, /a/, and /u/ were used as these represented the most extreme articulatory positions for vowel formants (Liberman & Blumtein, 1988). Thus, the F1 and F2 measurements of these vowels could be used to calculate an individual's "vowel space". The consonants /s/, /b/, and /g/ were used because /s/ was identified as a problem sound for HI children and the selection of the three consonants would allow for a sample of comparisons between voiced (/b, g/) and voiceless (/s/); between fricative (/s/) and plosive (/b, g/), and between different places of articulation, including bilabial (/b/), alveloar (/s/), and velar (/g/). The three words for each consonant context were repeated five times in random order. In total, the word list was comprised of 45 words (3 vowels X 3 consonants X 5 trials).

2.3 Participant's task

The participant was asked to say the words in the Goldman-Fristoe test and the 45-word list once, as they normally would say them and then repeat the 45-word list using a more open mouth posture. Each word was presented separately in written form on a piece of A4 paper. For the open-mouth task, the experimenter verbally gave the instruction, “read the list again, but this time think about having a more open mouth”, and provided a real-life demonstration.

2.4 Instrumentation

A multi-channel digital recording system was set up to record acoustic and EGG signals and marker-based video tracings of jaw and lip movements.

2.4.1 Simultaneous Acoustic and EGG recording

A laptop (HP Compaq nx7400, Taiwan) equipped with a 12-bit multichannel A/D converter (National Instrument DAQCard-AI-16E-4, USA) was used to record the acoustic and EGG recordings simultaneously on separate channels. The acoustic recording device consisted of a headset condenser microphone (AKG C420, Austria) and a mixer (Eurorack MX602A, Behringer). The EGG device (Kay Elemetrics Model 6103, USA) consisted of two round-shaped electrodes (3.5 cm in diameter) and a processor. The output of the acoustic device and the output of the EGG device were connected to the A/D converter via separate channels using a SCB-68 68-pin shielded connector box. The connector box housed two filters to low-pass the acoustic signals at 20 kHz and the EGG signals at 5 kHz, separately. The sampling rate for digitization was set at 44 kHz. For the digitization of the acoustic and EGG signals and the anaylsis of the EGG signals, a locally developed algorithm written in MATLAB 6.0 (The Mathworks, Inc., USA) was used. For analysis of the acoustic signals, a time-frequency analysis software (TF32; copyright: Paul Milenkovic, 2000, USA) was used.

2.4.2 Marker-Based Video Facial Tracking

A second laptop (Acer Aspire 5570Z, Taiwan) was used to record the marker-based video facial tracking signals. The marker-based video facial tracking system consisted of a mini camera (1/4 CMOS PC Camera, Taiwan) with two infrared light-emitting diodes on both sides of the camera. The camera was mounted on a wooden board secured on a tripod placed in front of the participant. Eight six-millimetre dots, cut from a reflective adhesive material, were placed on the participant's face. Four dots were placed on the right and left sides of the mouth, on the tip of the nose, and on the chin respectively. Four dots, which were adhered to a small 4 cm X 4 cm square cardboard taped to the forehead, were used as the calibration reference. Video images of the tracings of the reflective dots were acquired and processed using a locally developed programme written in C++.

2.5 Procedures

Each participant was seated individually in a quiet room. The experimenter placed the headset microphone over the participant's ears, with the microphone placed off-axis approximately 5 cm away from the mouth. The EGG electrodes were placed on the skin over the two thyroid alae and held in place with a Velcro strap. The the light-reflecting dots were put in the places as previously mentioned. The blinder containing the reading material was placed in front of the participant at eye level from a distance comfortable to the participant. After all the equipment was in place, the participant was asked to vocalize the vowel /a/ to allow the experimenter to adjust the recording level for the microphone signals, the placement of the EGG electrodes, and the camera. Once the experimental setup was optimized, the participant was asked to perform the participant's task. During recording, one experimenter was responsible for operating the recording system while the other instructed the participant and flipped the pages of the reading materials. The participant was given a short break after at least finishing 36 tokens. The total length of recording time was approximately 30 minutes for each participant.

For the HI group, participants 13 to 15 were recorded only with the simultaneous acoustic-EGG system and only for the Goldman-Fristoe test. This was because recordings of these three participants were retrieved from an earlier recording, which was conducted using the same recruitment method and instrumentation (but without the facial tracking component), as mentioned above.

2.6 Measurement and Data Analysis

The experimental measures were obtained from three types of signals: acoustic, EGG, and video facial tracking of jaw opening. A description of these measures and the method used to derive them are as follows.

2.6.1 Acoustic Measures

Measures derived from the acoustic recordings of the vowels included: vowel length, F0, percent jitter (percent jitter), percent shimmer (percent shimmer), signal-to-noise ratio (SNR), F1, and F2. Acoustic measures for the consonants included: consonant length and spectral moments.

2.6.1.1 Vowel Length

To determine the vowel length, the time waveform and the spectrogram of the acoustic signal of the vowel were displayed in separate windows. The experimenter manually placed the cursors at the beginning and the end of the vowel to generate an automatic reading of the time duration of the selected segment. The placement of the cursors was adjusted based on the visual inspection of the display, with verification through listening to the playback of the selected segment when necessary.

2.6.1.2 Fundamental Frequency and Perturbation Measures

From the time waveform display of the vowel, a steady portion of the vowel was cursor-selected. The selected segment, with a length ranging from 40 to 200 ms, was processed using the “jitter” function of the TF32 to derive measures of F0, percent jitter, percent shimmer, and SNR.

2.6.1.3 Formants and Vowel Space

Formant frequencies were measured for all vowels (/i, a, u/) in the one or two-syllable word list and for vowels /i, a, u/ preceeding either a nasal or oral consonant in the Goldman-Fristoe test. On the display of the spectrogram, a cursor was moved to the mid steady-state portion of the vowel to select one time slice. A LPC (Linear Prediction Coding) spectrum of the time slice chosen was displayed on a separate window and an automatic peak picking algorithm was used to determine the frequencies of F1 and F2. The formant frequencies for the vowels /i, a, u/ were used to calculate the area of the vowel space. This formula for calculating the vowel triangle was:

Area (Hz^2) = ABS {[F1i*(F2a-F2u) + F1a*(F2u-F2i) + F1u* (F2i-F2a)]/2}, where "ABS" represents the absolute value, "F1i" means F1 value of vowel /i/, etc (Lui et al., 2003).

2.6.1.4 Voice Onset Time/Consonant Length

As previously described, C-Length was measured as the length between the release of the plosive to the onset of the vowel. Based on visual inspection of the display of the time waveform and the spectrogram, the experimenter placed the cursors at the beginning and the end of a consonant to give a time measurement.

2.6.1.5 Spectral Moments

The word-initial consonants /s/, /b/ and /g/ were analyzed using spectral moment analysis. For each consonant this yielded moment one (M1), which represents the mean frequency, around where the spectral energy is concentrated, moment two (M2), which represents the standard deviation or spread of the energy, moment three (M3), which represents the skewedness of the spectral energy, and moment four (M4), which represents the peakedness of the spectrum.

2.6.2 Electroglottography

Measures of SQ and OQ were derived from EGG signals to reflect the pattern of vocal fold vibration. A segment of 5,000 sample points (equivalent to 113.6 ms) of the EGG waveform was selected from the target syllable for an automatic calculation of F0, OQ, and SQ. A 90% method was used to define the various phases in a glottal cycle. The time between 10 and 90% of the whole amplitude range of a glottal cycle, during glottal opening, was defined as the opening phase (Lim et al., 2006).

2.6.3 Marker Bases Video facial tracking

To derive measures of maximum jaw displacement, the time waveform of the video-tracking signals was displayed on a computer screen. The tracing for jaw opening represents changes of the distance between the dots on the chin and on the nose, with a higher value indicating a larger degree of jaw opening. The tracing for lip spreading represents changes of the distance between the dots on the two sides of the mouth, with a higher value indicating a larger degree of lip spreading. During video recording, the displacement values were automatically calibrated against the reference dots placed on the forehead, and thus the displacement values were shown as real-life size. With confirmation through visual inspection of the presence of the time-aligned tracing of lip spreading, the experimenter identified the highest peak of the jaw movement and cursor-selected the peak to obtain the reading of its magnitude. The value for the maximum jaw placement was recorded in a spreadsheet, along with the baseline jaw movement (indicating jaw at rest). The extent of jaw opening was then automatically calculated as the difference between the maximum displacement and the baseline measures.

2.7 Statistical analysis

A series of two-way analysis of variances (ANOVAs) was performed on individual participant's data for each vowel separately, to determine whether there was a jaw effect (normal versus open jaw), consonant effect, or a consonant-by-jaw interaction effect on the experimental measures. A series of two-way Repeated Measures (RM) ANOVAs was performed on the average values obtained from individuals in the normal-hearing group to examine the general effects of the independent variables for the normal-hearing group. Post-hoc pairwise multiple comparison procedures using the Holm-Sidak method were conducted when a significant effect was detected. The significance level was set at 0.05. SigmaStat 3.5 (Systat Software, Inc., USA) was used for all statistical analysis.

Chapter 3. Results

Results of a series of two-way ANOVAs performed for individuals in the normal-hearing group were shown in Appendices to 6 to 18. Results of a series of two-way Repeated Measures ANOVAs perfomed for the normal-hearing group as a whole were shown in Table 5. Results of a series of two-way ANOVAs performed for the three HI participants (HIF1, HIF2, HIM1) separately were shown in Tables 6 to 10.

3.1 Formant Frequencies and Vowel Area

Specific findings relating to the effect of jaw opening and consonant context on measures of F1, F2, and vowel area were described as follows. The F1-F2 vowel plots using the formant frequencies averaged for the normal-hearing group were shown in Figure 1. The F1-F2 vowel plots for the three HI participants (HIF1, HIF2, and HIM1) were shown in Figure 2.

3.1.1 Jaw Effect

For the normal-hearing group as a whole, as shown in Table 5, the jaw effect on F1 was not found significant in any vowel context. With male and female normal-hearing groups analyzed separately, there remained no significant jaw effect on F1. However, for the two female HI participants (HIF1 and HIF2), a significant jaw effect, along with a significant consonant by jaw interaction effect, was found on the F1 measure of the vowel /a/ (Table 6). Post-hoc tests revealed that the F1 of the vowel /a/ in the open jaw condition was signficantly different than that in the normal jaw condition only in the /b/ context for HIF1 and only in the /s/ and /g/ contexts for HIF2, with F1 being higher in the open jaw condition (Figure 2.2). A significant jaw effect on F1 for the vowel /u/ was found in both H1F2 and H1M1 (Table 6), with the open jaw condition resulting in a lower F1 in H1F2 but a higher F1 in H1M1 as compared with the normal jaw condtion (Figure 2.2). For the hearing impaired male participant (HIM1), a significant jaw effect on F1 was also found for the vowels /i/ (Table 6), with a lower F1 associated with the open jaw condition for the vowel /i/ (Figure 2.2).

As for F2, the normal-hearing group showed a significant jaw effect on F2 for the vowel /i/, with the open jaw condition leading to a higher F2 than the normal jaw condition (Figure 1.1). For the hearing-impaired group, a significant jaw effect on F2 was found in the vowel /i/ for the hearing impaired male HIM1 (Table 6), with a higher F2 associated with the open jaw condition (see Figure 2.2). A signficant jaw effect, as well as a significant consonant by jaw effect, on F2 was found in the vowel /a/ for HIF2. Post-hoc tests revealed that in the vowel /a/ for the hearing impaired female HIF2, F2 in the open jaw condition was signficantly lower than that in the normal jaw condition but only in the /s/ and /g/ contexts.

As shown in Figures 1 and 2, the changes in formant positions resulted in the expansion of vowel area for the open jaw condition as compared with normal articulation. For both normal hearing (Figure 1.1) and hearing-impaired groups (Figure 2.1), the average vowel area was greater in the open jaw condition (Normal-hearing: 257,568 Hz^2, Hearing impaired: 172,921 Hz^2) than in the normal jaw condition (Normal-hearing: 233,798 Hz^2, Hearing impaired: 97,914 Hz^2).

3.1.2 Consonant Effect

For the normal-hearing group, as shown in Table 5, a significant consonant effect was found for both F1 and F2 but only in the vowel /a/, with the /s/ context being associated with significantly lower F1 than both /g/ and /b/ contexts (Appendix 19.2) and significantly lower F2 than the /g/ context (Appendix. 20.2).

For the HI participants, as shown in Table 6, a significant consonant effect on F1 was found in all three HI participants for the vowels /i/ and /a/. With the vowel /i/, F1 was significantly lower in the /g/ context than that in both the /s/ and /b/ contexts for both HIF2 and

HIM1 and significantly higher in the /s/ context than that in the /b/ context for HIM1 (Appendix 19.1). Tests following up the consonant by jaw interaction effect in HIF1 for the vowel /i/ revealed that the consonat context /g/ resulted in a signficantly higher F1 than both /s/ and /b/ contexts but only in the open jaw condition (Appendix 19.1). As for F2 in the vowel /i/, a significant consonant effect was found for all three participants in the HI participants, with F2 being significantly higher for HIF1 and lower for HIM1 in the /s/ context than in the /b/ context (Appendix 20.1).

For the vowel /a/, a significant consonant effect was found for all the three HI participants, with the F1 in the /s/ context being significantly lower than that in both /g/ and /b/ contexts, as was found in the normal-hearing group, except that F1 in the normally articulated /b/ context for HIF1 and in the /g/ context for HIM1 were not found significantly different from the /s/ context (Appendix 19.2). As for F2 in the vowel /a/, a significant consonat effect was found for all the three HI participants, with F2 in the /s/ context being significantly lower than in the /g/ context (Appendix 20.2).

For the vowel /u/, a significant consonant effect was found for F1 in two HI participants (HIF2 and HIM1), with F1 being significantly higher in the /s/ context than in the /g/ context (Appendix 19.3). As for F2 in the vowel /u/, a signficant consonant effect was only found for the hearing impaired male (HIM1), with F2 being significantly higher in the /g/ context than in both /s/ and /b/ contexts (Appendix 20.3).

3.2 Fundamental Frequency

For the normal-hearing group as a group, as shown in Table 5, the jaw effect on F0 was not found significant in any vowel context. However, a closer examination of the results from a secondary analysis of individuals's data from the normal hearin group revealed that some normal-hearing participants did show a jaw effect on F0 (Appendix 8), with the open jaw condition resulting in a significantly higher F0 than the normal jaw condition in most participants except that in three cases, including F3 (/a/ and /u/) and M2 (/u/), the open jaw condition showed a significantly lower F0 than the normal jaw condition. For the HI participants, as shown in Table 6, a significant jaw effect on F0 was found in HIF1 for vowel /i/ and in HIF2 for both vowels /a/ and /u/, with F0 being significantly higher in the open jaw condition than in the normal jaw condition (Figure 3).

For the normal-hearing group, a significant consonant effect on F0 was found in vowels /i/ and /a/ (Table 5). For the hearing-impaired participants, a significant consonant effect on F0 was also found (Table 6). Post-hoc tests revealed that the F0 meaasure of /a/ in the normal-hearing group was signficiantly higher following /g/ than following both /s/ and /b/ (Figure 4.2). For vowels /i/ and /a/ in the hearing-impaired participants, vowels following /g/ were also found to exhibt a higher F0 than those following /s/ or /b/ (Figures 4.1 and 4.2).

3.3 Perturbation Measures

Results concerning the effect of jaw opening and consonant context on measures of perturbation measures, including percent jitter, percent shimmer, and SNR, were described as follows.

3.3.1 Jaw Effect

For the normal-hearing group, as shown in Table 5, the jaw effect on percent jitter and percent shimmer were not found significant in any vowel context but a significant jaw effect on SNR was found for the vowel /a/, with the open jaw condition leading to a higher SNR than the normal jaw condition (Figure 9.2).

For the HI group, as shown in Table 7, a significant jaw effect was found on percent jitter for the consonant /u/ in one hearing impaired female (HIF2), with a significantly higher percent jitter in the open jaw condition as compared with the normal jaw condition (Figure 5.3). A significant jaw effect on percent shimmer was found in one hearing impaired male (HIM1) for the vowel /i/ and in two hearing-impaired participants (H1F2 and H1M1) for the vowel /u/ (Table 7), with percent shimmer being significantly higher in the open jaw condition than in the normal jaw condition (Figures 7.1 and 7.3).

A significant jaw effect on SNR was found in all hearing-impaired participants for the vowel /u/ (Table 7), with SNR being higher in the open jaw condition than in the normal jaw condition for H1F1 but lower for H1F2 and H1M1 (Figure 9.3). For vowels /i/ and /a/, SNR was found to be significantly lower in the open jaw condition than in the normal jaw condtion for H1F2 (Figure 9.1) and H1M1 (Figure 9.2).

3.3.2 Consonant Effect

For the normal-hearing group, as shown in Table 5, a significant consonant effect was found on all perturbation measures for the vowel /u/ and on SNR for the vowel /i/, with percent jitter and percent shimmer being significanly lower (Figures 6.3 and 8.3) and SNR being significantly higher (Figure10.3) in the consonant /s/ context than in the /b/ context (Figure 6.3).

For the HI participants, as shown in Table 7, a significant consonant effect was found on all perturbation measures for the vowels /i/, /a/, and /u/. For the vowel /i/, all HI participants (HIF1, HIF2 and HIM1) showed a significanlty higher percent jitter (Figure 6.1) and percent shimmer (Figure 8.1) in the /g/ context than in the /s/ or /b/ context. For the vowel /a/, percent jitter was significanly higher in the /g/ context than in the /b/ context for HIF2 and than in the /s/ context for HIM1 (Figure 6.2) while these two hearing-impaired participants (HIF2 and H1M1) also showed a significantly higher percent shimmer in the /g/ context than in the /b/ context (Figure 8.2). Similarly, for the vowel /u/, these two hearing impaired female participants (HIF2 and HIM1) showed a significantly lower percent jitter in the /s/ context than in both /g/ and /b/ contexts (Figure 6.3) while all hearing-impaired participants showed a significantly lower percent shimmer in the /s/ context than in the /b/ context (Figure 8.3). As for SNR, the /s/ context resulted in a significantly higher SNR than the /g/ or /b/ context for most of the hearing-impaired participants for all vowels (Figure 10).

3.4 Temporal Measures

Specific findings relating to the effect of jaw opening and consonant context on measures of vowel and consonant length were described as follows.

3.4.1 Vowel Length

For the normal-hearing group, a significant jaw effect on vowel length was found for all vowels (Table 5), with an open jaw condition resulting in a longer vowel length than the normal jaw condition (Figure 11). The same jaw effect on vowel length was found on some HI participants for the vowels /i/ and /a/ (Figures 11.1 and 11.2) but not in any HI participant for the vowel /u/ (Table 8). A significant consonant effect on vowel length was found in all vowels for the normal-hearing group (Table 5) and all the three HI participants (Table 8). For vowels /i/ and /a/, vowel length in the consonant /b/ context was found to be significantly longer than that in the /g/ context (Figures 12.1 and 12.2). For the vowel /u/, vowel length in the consonant /s/ context was significantly longer than that in both /g/ and /b/ contexts (Figure 12.3).

3.4.2 Consonant Length

For the normal-hearing group, no signficant jaw effect on consonant length was found (Table 5). For one HI participant (HIF2), a significant jaw effect, along with a signficant consonant by jaw interaction effect, was found for vowels /i/ and /u/ (Table 8), with the open jaw condition resulting in a shorter consonant length (Figures 13.1 and 13.3). A significant consonant effect on consonant length was found for the normal-hearing group (Table 5) and all the three HI participants (Table 8), with the /s/ context leading to a significantly longer consonant length than both /g/ and /b/ contexts (Figure 14).

3.5 Spectral Moments

No signficant jaw effect on M1 or M2 was found in the normal-hearing group (Table 5). A significant jaw effect on M1 was found in some HI participants (Table 9), with the open jaw condition resulting in a significantly higher M1 for H1F2 in vowels /a/ and /u/ (Figures 15.2 and 15.3) but a significantly lower M1 for H1M1 in the vowel /u/ (Figure 15.3) as compared with the normal jaw condition. A significant jaw effect on M2 was found for the vowel /u/ in one hearing-impaired participant (H1F1), with the open jaw condition resulting in a significantly lower M2 than the normal jaw condition. A signficant consonant effect on M1 was found for all vowels in the normal-hearing group (Table 5) and all HI participants (Table 9), with /b/ exhibiting a significantly lower M1 as compared with /g/ and /s/ (Figure 16). For all vowels, M2 was consistently found to be signficantly highest for /b/, followed in order by /g/ and /s/ (Figure 16).

3.6 Open Quotient and Speed Quotient

No significant jaw effect was found significant on OQ or SQ for the normal-hearing group (Table 5). A significant consonant effect on OQ and SQ was found for the vowel /a/ in the normal-hearing group (Table 5) but post-hoc tests failed to reveal any signficant difference between the three consonant contexts. A closer examination of the results from a secondary analysis of individuals's data from the normal hearin group, as shown in Appendix 16, revealed that for the vowel /i/, a significant jaw effect was found in only one male hearing participant (M2), who had a significantly higher OQ in the open jaw condition (Mean = 0.34, SD = 0.02) than in the normal jaw condition (Mean = 0.30, SD = 0.04). For the vowel /a/, however, another normal-hearing participant (M5) showed a signficantly lower OQ in the open jaw condition (Mean = 0.25, SD = 0.02) than in the normal jaw condition (Mean = 0.27, SD = 0.03) and a significantly higher SQ in the open jaw condition (Mean = 0.69, SD = 0.02) than in the normal jaw condition

(Mean = 0.67, SD = 0.04). Due to missing data, the effects of jaw and consonant context on OQ and SQ could not be assessed for the HI participants.

3.7 Maximum Jaw Diaplacement

As shown in Figure 19, the open jaw condition generally resulted in a greater degree of maximum jaw displacement than the normal jaw condition. However, a significant jaw effect on the measure of maximum jaw displacement was shown only in the vowel /a/ for the normal-hearing group (Table 5). For the hearing-impaired participants, a significant jaw effect on the measure of maximum jaw displacement was found in all three participants for the vowel /a/ and in H1F2 for the vowel /i/ and in H1F2 and H1M1 for the vowel /u/ (Table 10). A significant consonant effect on the measure of maximum jaw displacement was found in the normal-hearing group for the vowel /a/ (Table 5), with the bilabial (/b/) context showing a significantly largest maximum jaw displacement, followed in order by the velar (/g/) and alveolar (/s/) contexts. A significant consonant effect on the measure of maximum jaw displacement was also found for all the three hearing-impaired participants for the vowel /a/ (Table 10), with the alveolar (/s/) context showing a significantly smaller maximum jaw displacement than both bilabial (/b/) and velar (/g/) contexts (Figure 20.2). For the vowel /i/ in H1F2, the velar (/g/) context was found to yield a significantly smaller maximum jaw displacement than both /s/ and /b/ contexts (Figure 20.1).

3.8 Comparison of Correct and Incorrect Articulation in the Goldman-Fristoe Test

Misarticulated consonants identified from recordings of the Goldman-Fristoe Test of Articulation included devoicing in H1F1 (i.e., /d/ misarticulated as /t/), devoicing combined with frication in H1F3 (i.e., /d/ misarticulated as /s/), palatalization in H1F3 (i.e., /s/ misarticulated as /sh/), and fronting in H1M1 (i.e., /s/ misarticulated as /th/). Results from a comparison of M1 and M2 measures between the correct production obtained from the normal-hearing group and the misarticulated productions from the hearing-impaired participants revealed that M2 measures tended to be higher in the misarticulated consonants than in the correct productions and M1 measures tended to be higher with devoicing, frication, and fronting (Appendices 21 and 22).

3.9 Summary of Main Findings

The main findings of this study were sumarized as follows:

1. Jaw effect: As compared with the normal jaw condition, an open jaw posture was found to result in a larger extent of maximum jaw displacement, increased vowel length, and vowel-dependent changes of F1 and F2 leading to expansion of vowel space regardless of the hearing status. Fundamental frequency, percent jitter, and percent shimmer were found to be unaffected by the jaw opening posture in the normal-hearing group. However, F0, percent jitter, and percent shimmer showed some increase with the open jaw condition in some hearing-impaired participants. As for SNR, although remaining within normal limits with or without an open mouth posture, SNR was found to improve with the open jaw condition for the normal-hearing group in general and for one hearing-impaired participant (H1F1) but worsen for two hearing-impaired participants (H1F2 and H1M1).
2. Consonant effect: Consonant effect was found significant for all experimental measures except for OQ and SQ. In particular, maximum jaw displacement was found to be affected by the place of articulation, with the alveolar sound /s/ leading to smaller jaw disaplacement than bilabial (/b/) and velar sounds (/g/). The consonant length was affected by the manner of articulation, with the voiceless fricative (/s/) showing a longer consonant length than the voiced plosives (/g/ and /b/).
3. Effect of Hearing impairment: As compared with the normal-hearing participants, the HI participants exhibited smaller vowel areas in the normal jaw condition but showed

a relatively greater expansion when asked to speak with an open mouth. When producing speech with an open mouth, the normally hearing group showed a small expansion of vowel space mainly through the increase of F2 frequency in the vowel /i/ while the HI participants through not only the increase of F2 frequency in the vowel /i/ but also the lowering of F1 frequency in the vowel /i/, the raising of F1 frequency in the vowel /a/, and the lowering of F2 frequency in the vowel /a/.

Chapter 4. Discussion

The purpose of this study was to investigate the use of open mouth, or open jaw, articulation as a facilitative strategy to improve the speech and voice of children with prelingual hearing impairment. It also aimed to add to the body of knowledge regarding the speech production characteristics of children with and without hearing loss, using objective methods of analysis. This chapter provides a discussion of outcomes in relation to the reasearch questions and hypotheses, and in regards to previous research. Clinical implications, limitations, and directions for future research are also discussed.

4.1 Related to Research Questions

The research questions, as stated previously, concerned whether an open jaw posture could facilitate an increase the vowel area and vocal stability of children with hearing impairment. The question was also raised as to what differences were present between HI and normal hearing children's speech and voice characteristics, especially when using the open jaw technique. It was hypothesized that an open jaw posture would improve vowel area and vocal stability. It was also hypothesized that HI participants would have smaller vowel areas than their normal-hearing peers and thus would consequently show a greater level of improvement with the open jaw approach. Findings from this study, as evidenced through objective measures of speech and voice, have shown positive effects of open jaw articulation in the expansion of vowel space and in increased vocal stability.

Specifically, it was hypothesised that an open jaw posture would facilitate movements of F1 and F2, resulting in a larger vowel area. The present findings supported this hypothesis. With an open jaw posture, many participants were found to show significant movement of F1 and F2 resulting in increased vowel area regardless of the hearing status. In addition, as hypothesized, consonant immediately preceding the vowel had a significant effect on the formant measures of the following vowels. As discussed previously, F1 relates to tongue height, with lower F1 values being associated with higher tongue position (Perkins & Kent, 1986). The vowel /a/ was found in this study to have a lower formant 1 value when it was preceded by the consonant /s/. Producing the alveolar consonant /s/ requires a high tongue position with the tongue tip touching the alveolar ridge (Davenport & Hannas, 1998). Therefore, it appeared that following /s/, the tongue position for the vowel /a/ was not as low as it would be when following /g/ or /b/, contributing to a lower F1 measure. For the HI participants, the vowels /i/ and /u/ generally contained lower F1 values when preceded by /g/. This could be due to the place of articulation of the velar consonant /g/. To articulate a velar consonant, the back of the tongue is raised to the soft palette, close to that which is required to produce high vowels such as /i/ and /u/ and thus leading to lower F1. As for Formant 2, it was found to be higher in the high vowels /i/ and /u/ following the consonant /s/ than following /g/ and /b/. Formant 2 relates to tongue fronting, with front vowels having higher F2 values (Perkins & Kent, 1986). As /s/ is produce with more anterior tongue position than /g/ and /b/, the tongue is already fronted whereas /b/ and /g/ require forward movement.

It was hypothesised that an open jaw posture would increase vocal stability as shown by lower perturbation measures and increased SNR. As hypothesised, open jaw posture facilitated an increase in SNR for the normaly hearing pairtipants for the vowel /a/ and in one HI participant for the vowel /u/. However, contrary to the hypothesis, an increase in jitter and shimmer measures were shown in some HI participants with an open jaw posture. It was speculated that this could be attributed to a greater extent of uncertanty and thus instability for the HI children in mantaining the coordination between the jaw and the laryngeal musculatures when attempting an open jaw posture for high vowels.

As hypothesised, the consonant preceding the vowel was shown to have an effect on perturbation measures and SNR. In general, the consonant /s/ was associated with an improvement in percent jitter, percent shimmer, and SNR while the consonant /b/ was generally associated with higher perturbation and decreased SNR. This finding was expected as it was anticipated that a voiceless consonant would set the vocal folds in an open and thus less constricted condition, which was conductive to the stability in the vocal fold vibration required for producing the following vowel.

It was hypothesised that HI participants would show a greater level of improvement with the open jaw approach, as they would have smaller vowel areas than their normal-hearing peers to begin with. The present findings supported this hypothesis as the HI participants showed more restricted vowel areas than their normal-hearing peers, especially with the HI male showing the most restricted vowel area. This led to a larger expansion of vowel area, when using open jaw articulation, in comparison to the normal hearing speakers. In addition, a higher proportion of significant changes in formant frequency were facilitated for the HI speakers.

4.2 Related to Previous Reseach

The following sections detail the findings of this study in relation to previous research, including formants and vowel space, temporal measures, spectral moments, vocal characteristics, and jaw displacement. Due to the use of a simultaneous multi-channel recording method in this study, comparison of a variety of experimental measures with other studies is possible. This gives a better insight into the utility of open jaw posture and the characteristics of children's speech.

4.2.1 Formants, Vowel Space, and Intelligibility

The analysis of Formants 1 and 2 were included in this study to provide information on tongue movement associated with the vowels /i/, /a/ and /u/ when produced with normal and open jaw postures. As discussed previously, F1 and F2 relate closely to tongue position along the dimensions of height, with a lower F1 being associated with a higher tongue position, and front-backness, with a higher F2 corresponding to a fronted tongue position (Perkins & Kent, 1986). The plotting of Formants 1 and 2 from each of the vowels /i/, /a/, and /u/ allowed for a comparison of vowel area between normal and open jaw conditions. Previous studies have used vowel area to assess the effectiveness of training programs. As mentioned earlier, Monsen & Shaughnessy (1978), in a study of F1/F2 vowel plots with five different vowels, found that following their training program, HI children produced larger, more distinct vowel areas. The present study found larger vowel areas, with open jaw posture, for both HI and normal-hearing participants. This is consistent with studies such as Smiljanić & Bradlow (2005) who studied the effects of "Clear speech" in English and Croatian. As discussed previously, "Clear speech" is an exaggerated form of articulation in which the speaker purposefully speaks in a way that will convey the message as accurately and as clearly as possible to the listener. Like the open jaw technique, this involves consciously modifying one's speech. Bond & Moore (1994) studied the acoustic characteristics of five speakers (each reading the same passage) who were rated for intelligibility by native and non-native speakers. Speakers who were rated as least intelligible had the smallest vowel areas (as measured by F1 and F2) and shortest vowel durations. As previously mentioned, Turner et al. (1995) found an increase in intelligibility corresponded to an increase in vowel area for speakers with ALS. Therefore, while perceptual evaluations of intelligibility are not available for the present study, the increase in vowel area, as seen in the open jaw condition, is likely to correspond with improved intelligibility.

The present finding that the HI participants had a more restricted vowel area than the normal hearing group is consistent with Angelocci et al. (1967) who found more overlapping of vowel areas for deaf subjects than for normal-hearing subjects. Angelocci et al. (1967) used a sound spectrography to measure the formants and vowel areas of two groups of 18 eleven-to-fourteen-year-old male subjects, with or without hearing loss (thresholds above 60 dB), while reading a list of ten sentences targeting ten different vowels. Not only did they find reduced vowel areas for HI subjects, they also found that the areas in which given vowels were articulated was more variable when compared with the normal-hearing subjects. Consequently, due to less distinction in vowel production area, the HI subjects were more likely to be perceived less intelligible (32 percent intelligible) than the normal-hearing subjects (82 percent intelligible) in their articulation of vowels.

Hocevar-Boltezar, Boltezar & Zargi (2008) studied the acoustic changes of the corner vowels in 12 postlingually deaf adults and 13 prelingually deaf children following cochlear implantation. The CI allowed them access to the frequencies most important for speech. The children showed an increase in vowel area compared to six months earlier, illustrating the potential positive outcomes with the use of cochlear implants. The adults showed no significant change in vowel area. Like the present study, this study showed the benefits of using objective analysis following the introduction of a device, such as a CI or a training procedure. As the aim is to improve speech, vowel area, as measured by F1 and F2, can provide objective evidence of physical change in articulation. In the present study, the HI male, who had the most elevated hearing thresholds among the participants, showed the smallest vowel area for the vowels /i/, /a/ and /u/. This agrees with the previous finding that the degree of hearing loss was related to the level of speech problems (Hudgins & Numbers, 1942; Smith, 1973; Boothroyd, 1984).

The average formant measures of the vowels /i/, /a/, and /u/ in the present study are relatively comparable to average formant values for adult speakers of New Zealand English (Maclagan 1982 in Bauer & Warren, 2004). However, the formant measures in the current study were taken from children. Since children have smaller vocal tracts than adults (Vorperian & Kent, 2007), differences between studies are most likely to be the result of differences in vocal tract length.

4.2.2 Temporal measures

The present finding indicates that vowel length increases with open jaw articulation, at least for the vowels /i/ and /a/. The act of opening the mouth more, as in the open jaw condition, may indirectly slow speaking rate, as manoeuvring of the mandible to a greater degree requires more time. This in itself may improve the clarity of speech. Smiljanić & Bradlow (2005), in a study of 'clear speech' in Croatian and English, found a decrease in speaking rate when using the technique, contributing to an increase in intelligibility scores. The tendency for the HI speakers to show shorter vowel lengths than the normal-hearing speakers, regardless of jaw opening, is consistent their speech being less intelligible. Bond & Moore (1994), as described above, found that speakers who were rated as least intelligible had the shortest vowel durations.

The voiceless fricative /s/ exhibited the longest consonant duration. This agrees with the literature which showed that voiceless sounds tended to have longer duration before the onset of voicing than voiced sounds such as /g/ and /b/ (Lieberman & Blumstein, 1988). For the normal-hearing participants in the present study, the length of /s/ in the normal condition was 207 ms. This is comparable to Jongman, Wayland & Wong (2000) who conducted an objective study on the acoustic clues of place of articulation in fricatives. In Jongman et al.'s study, 20 university students were recorded saying eight different consonants in a CVC context. The average length of the consonant /s/ found in Jongman et al.'s study was 178 ms.

4.2.3 Spectral Moment Analysis

Spectral moment analysis was included in this study to assess the difference in the frequency distribution of consonants between normal and open jaw conditions as well as between HI and normal-hearing participants. The present findings indicate no significant effect of open jaw posture on M1 or M2 for the normal-hearing group. Spectral moment analysis of the HI participant's consonant are variable, with no clear pattern emerging. Figure 21 shows the mean and standard deviations of M1 of /s/ for the first three HI participants in comparison to the normal-hearing group. The consonant /s/ is often misarticulated by HI speakers as it contains very high frequency components (Northern & Downs, 2002). In this study, the HI productions of /s/ are generally within the range of the normal-hearing group, indicating correct production. While few statistically significant differences in spectral moments emerged between normal and open jaw conditions in the present study, previous studies have shown the utility of speech moments in the analysis of consonant features (Forrest et al., 1990; Tjaden & Turner, 1997; Nissen, 2005). Spectral moment analysis can reflect the appropriateness of articulator placement (Uchanski & Geers, 2003), as it has been shown to distinguish palce of articulation of certain consonants (Nissen (2005). For example a person with normal speech will have a higher M1 (the spectral mean) for /s/ than for 'sh'. Lowering of M1 when producing /s/ could indicate a more palato-alveolar tongue placement (rather than alveolar) aproaching the articultory area of 'sh'. This is likley to occur for HI speakers who can not percieve such a distinction due to high frequency hearing loss.

In the present study, spectral moment analysis of HI participants' misarticulated consonants in the Goldman-Fristoe Test of Articulation provided objective information on their frequency distribution (Figures 22-24). The misarticulated consonants were auditorily decerned as being incorrect. Spectral moment analysis gives objective information on what makes them sound incorrect. Although there were insufficient tokens with which to compare the HI and normal-hearing groups, descriptive comparisons can be made. As shown in Figures 22-24, the M1 were noticibly higher, or lower, than that obtained from the normal-hearing group. In addition the M2, or spectral variance, was greater for the HI productions compared to the normal-hearing group's productions. For example, Figure 23 shows that an HI participant's /s/ production in the word 'santaclause' showed an M1 of 12.2 kHz and an M2 of 5.5 kHz, while the normal hearing male group produced the equivalent consonant with an M1 of 8.4 kHz and and M2 of 2.5 kHz. It is known that formant frequencies of fricatives rise as the place of articulation moves anteriorly in the mouth (Davenport & Hannahs, 1998). The high mean frequency value shown in the M1 measure of /s/ for this HI participant indicates that the place of articulation was closer to that of a dental fricative 'th' than an alveolar /s/ consonant. These observations are supported by other studies which show that spectral moments are useful to distinguish where consonants are articulated. Nissen (2005) studied the ability of acoustic analysis to distinguish the place of articulation for voiceless fricatives. Thirty children (aged 3 to 6) and 10 adults, without hearing or speech pathology, were recorded saying words containing /s/, 'sh', /t/, and 'th' before the vowels /i/, /a/, and /u/ yielding a total of 60 tokens per participant. Analysis of the spectral moments of the four different voiceless fricatives revealed that spectral variance (M2) could successfully distinguish place of articulation for all four consonants. Uchanski & Geers (2003), in a study outlined previously, used acoustic analysis, including spectral moments, to examine the speech features, of children aged 8 to 9, associated with using a cochlear implant in comparision to normal-hearing. Cochlear implant users were using either the total communication or the oral method of communication. It was found that the spectral mean (in barks) for the consonant /s/ was 19.4 for the normal speakers compared to 18 for the cochlear implant users in the total communication (TC) group, and 18.7 for those in the oral group. Therefore the HI participants in this study were shown to produce /s/ in a way that the distribution of the acoustic energy was closer to the acoustic area of 'sh' (with values of 17.6, 17.7 and 17.6 barks for the TC oral and normal groups respectively) as compared with the normal-hearing speakers (Uchanski & Geers, 2003). It is known that the consonant /s/ tends to have spectral peaks at very high frequencies, generally with a spectral peak in the range of 4-5 KHz (Davenport & Hannahs, 1998; Jongman et al., 2000). In the present study, the normal-hearing participants M1 of /s/ had an average of 9.6 kHz for females and 8.7 kHz for males.

Jongmanet al. (2000), in a study outline above, found that the mean M1 averaged across all participants and vowel contexts was 6.1 kHz for the consonant /s/. The higher values found in the current study could be due to the age of participants. While Jongmanet al. (2000) studied the adult population, the present study consisted of 9 to 12 year-olds.

4.2.4 Vocal Characteristics

Electroglotographic analysis was included in this study as it has been shown to provide information on vocal characteristics of normal and disordered voices (Jaeger, Frohlich, Ackermann, & Schonle, 2001; Jiang, Lin, & Hanson, 2000; Chernobelsky, 2002). For this study, no significant difference in SQ and OQ were found with the introduction of open jaw posture. However, measures obtained from the EGG analysis are based on limited data due to difficulty obtaining an adequate signal for analysis.

Measures of percent jitter, percent shimmer, and SNR were included in this study to assess the effect of open jaw posture on vocal stability. Improvement in vocal stability is indicated by a decrease in jitter and shimmer measures and an increase in SNR (Gelfer, 1995). The present findings indicate that open jaw posture did not facilitate a significant decrease in the jitter and shimmer measures. However, SNR, in general, increased with open jaw posture, especially for the HI participants. Measures of SNR have been shown to be correlated with the perceptual rating of vocal pathology. In a study by Qi, Hillman, & Milstein (1999), trained vocal pathologists were asked to rate the clarity of speech, on a scale from normal to aphonic, of 87 participants with mild to severe vocal disorders. Acoustic measures of SNR were also taken from the recordings played to the listeners and correlated with the perceptual listener judgments of vocal pathology. It was found that SNR was correlated with listener judgments of vocal pathology, with highly disordered voices having lower SNR measures. Measures of SNR obtained in the present study, for the normal group, are similar to those obtained from normal speakers in previous studies. Gelfer (1995) (outlined above) studied the effects of vowel selection, frequency, and intensity on measures of jitter, shimmer, and SNR of 29 adult females. The vowels analysed in that study (/i/ and /a/) have comparable values for SNR to the present study. Gelfer (1995) found the SNR for /i/ and /a/, phonated at a moderate intensity, was 21.3 compared 22.1 respectively. It was found in the present study that for the vowels /i/ and /a/, signal-to-noise ratings were 20.6 and 19.3 respectively. Horri (1982) studied the difference in jitter and shimmer between eight English vowels using an accelerometer placed on the throat and found the average measure of percent jitter to be 0.71 for /i/, 0.72 for /a/, and 0.66 for /u/. These results are similar to the present finding that /i/ generally exhibited the highest percent jitter (Mean = 0.85), followed by /a/ (0.87), and /u/ (0.83).

The present study found that an increase in F0 generally accompanied the introduction of an open jaw posture, suggesting an increase in laryngeal tension. Shrivastav et al. (2000) found an increase in F0 when subjects used the yawn-sigh vocal stimulation technique prior to phonating the vowel /a/. As discussed previously, the yawn-sigh technique uses a yawn followed by a sigh to facilitate a relaxed vocal tract to reduce vocal hyperfunction (Boone, 1983). The authors suggest that an increase in laryngeal tension lead to a raised F0, even though this technique is commonly used to relax the larynx. The average fundamental frequency of the normal-hearing participants in this study is similar to that obtain in previous studies. Sorenson (1989) conducted an objective study of the F0 of children aged between 6 and 10 years old. Acoustic recordings were taken from three girls and three boys producing spontaneous speech, reading a selected passage, and producing sustained phonation of seven vowels. A 300-ms long segment extracted from each vowel was analysed using an automatic F0 analyser. They found that sustained vowel production produced higher F0 values compared to spontaneous speech and oral reading. In addition, no significant differences in F0 were present between girls and boys. With the production of high vowels, F0 was higher than with low vowels. This was attributed to the greater tension produced in the larynx with the production of high vowels (Sorenson, 1989). In the present study, higher F0 values were also associated with the high vowels /i/ and /u/ compared to the low vowel /a/. The methods used by Sorenson (1989) are similar to the current study. Therefore, the slightly higher measures found in that study are likely due to the age of participants. The children in Sorenson's study included children as young as six and a mean age of 8 years. The present study included participants between 9 and 12 years. These speakers are more likely to have higher mean F0, as F0 decreases with age (Vorperian & Kent, 2007). This is reflected by the slightly higher mean fundamentally frequencies for both girls and boys in Sorenson's study as compare with the present study.

4.2.5 Jaw Displacement

Analysis of the facial tracking of jaw displacement revealed that participants did increase their level of jaw opening during the open jaw task, particularly for the vowel /a/. This finding is important as it shows that improvement in vowel area and SNR, in the open jaw task, is related to the physical level of jaw opening. A consonant effect was found for the alveolar fricative /s/ exhibiting smaller jaw displacement than bilabial (/b/) and velar stops (/g/). This is consistent with previous research. Mooshammer, Hoole, and Geumann (2006) used electromagnetic midsagittal articulography to study the tongue and jaw coordination of five German-speaking adults for coronal consonants (s, 'sh' b, t, d, n, l). Consonants were produced in a VCV context, with the vowel /a/, in two conditions: normal (speaking at a comfortable level) and increased vocal effort (speaking as loud as possible without shouting). The sibilant and voiceless stops were found to be articulated with a lower degree of jaw opening than the other coronal consonants (b, d, n, and l). An increase of jaw opening reportedly resulted in increased vocal effort. Walsh and Smith (2002), in a study of 120 adults and children (as outlined above), found that the mean level of jaw displacement for the youngest participants (aged 12) was approximately 6 mm when averaged over the words "bob" and "pup". This finding is similar to the present study, as the maximum jaw displacement was between 5.2 and 9.1 mm when averaged over words containing the vowels /i/, /a/, and /u/.

4.3 Clinical implications

The present study provides objective evidence showing the positive effect of an open jaw posture on speech and voice. When asked to increase jaw opening during phonation, children produced speech exhibiting a larger vowel area and, in general, reduced SNR. It can be inferred from these findings that an open jaw posture assisted in increasing intelligibility for both hearing and HI children as intelligibility has been linked with increased vowel area (Angelocci et al., 1967; Turner, 1995; Smiljanić & Bradlowc, 2005). Therefore, this finding has strengthened the rationale behind the open jaw or open mouth approach. The positive outcomes for using an open mouth approach in the HI children supported the use of excessive jaw movement as a method of distinguishing vowels by HI speakers (Ling, 1976). Although the vowel areas produced by the HI participants in this study were generally smaller than those by the normal-hearing group, the vowels /i/, /a/, and /u/ were articulated in the same general area as the normal-hearing participants. This suggests that the open jaw technique is beneficial to HI children who at least maintain a distinction between vowels through correct tongue movement. The data provided in this study gives a foundation for further investigation into the use of open jaw technique in the HI population.

4.4 Limitations and future directions

While the present study has shown the usefulness of open jaw posture in speech and voice enhancement, there were some limitations. Firstly, the small number of HI participants did not allow for a group analysis with which to compare with the normal-hearing participants.

Therefore, it is difficult to generalise the findings to the HI population at large. Likewise, the sample size of the normal-hearing group was also small, limiting the level of generalisation that can be made in the normal-hearing population. A larger sample size would be needed in future studies so that the HI and normal-hearing participant groups would be better representative of the clinical and normal-hearing population. In addition, the inclusion of a number of participants with varying degrees of loss and speech production skills could lead to a better understanding of open jaw posture in relation to intensifying degrees of speech intelligibility. Secondly, while the inclusion of the Goldman-Fristoe Test of articulation allowed for a wide range of speech tokens, the number of trials for each token was limited. Therefore, although spectral moment analysis measures could distinguish correct and incorrect productions, these tokens could not be analysed for statistical significance. Thirdly, this study did not include perceptual evaluation of speech intelligibility, relying solely on objective measures to assess intelligibility. Future studies could also include perceptual evaluation of participant's speech in order to subjectively corroborate the use of objective measures in the identification of speech errors. Finally, while EGG has shown its utility in the literature (Dejonckere et al., 1995; Cheyne et al., 1999), there are some disadvantages for EGG including poor signal quality in those with small larynges such as women, children (Behrman, 2007). In the present study, it was not always possible to obtain EGG measurements due to participant characteristes, particularly for female participants. This has led to an incompleate data set making statitical comparsion between HI and normal groups difficult. Future studies should include a greater number of participants to limit the effect of individual characterisitcs and increase the proportion of obtainable EGG measurements.

4.5 Conclusion

This study employed a simultaneous recording technique and objective methods of analysis to investigate the effect of open jaw posture on the speech and voice of children with normal-hearing and with hearing impairment. For both groups, the use of open jaw posture was shown to facilitate an increase in vowel area and, to some degree, increased vocal stability. This supports the use of open jaw posture in a clinical setting. This study has provided evidence concerning the utility of objective measures of speech and voice and the benefit of open jaw posture in a HI paediatric population.

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TABLE 1. Characteristic speech and voice errors of the hearing impaired.

Study	Hearing Level	Characteristic Errors	Age	No.Participants in Study
Horii (1982b)	Moderate to severe	Higher fundamental frequency than normal-hearing peers	18-19	24
Elfenbein et al. (1994)	Mild to Moderate	Consonant substitution, distortion and omission	5-18	40
Hidgins & numbers (1942)	Mild to profound	Vowels substituted, distorted, neutralized diphthongized and nasalized	8-20	192
Ysunza & Vazquez (1993)	Profound	Resonance problems due to poor velopharangeal timing	14-20	53

TABLE 2. Studies utilitilising objective measures of speech and voice.

Measure	**Study**	**Population**
Spectrographic analysis	Monsen & Shaughnessy (1978); Ertmer (2001)	Hearing impiared children
Speech moment analysis	Tjaden & Turner (1997)	Adults with ALS
Perturbation measures	(Gelfer (1995)	Adults
Electroglottography	Jiang et al. (2000); Chernobelsky (2002); Dejonckere et al. (1995)	Adult singers
Jaw tracking	Tye-Murray & Folkins (1990); Ballard & Robin (2007)	Nerve paralysis- adults

TABLE 3. The spectrographic representation of consonants by manner of articulation

Consonants By Manner of Articulation	Spectrographic representation	Literature
Fricative consonants	High frequency, aperiodic energy	Davenport & Hannahs (1998)
Plosive consonants	A Vertical stripe of energy as the plosive is released followed by weaker aspiration noise	Perkins & Kent (1986)
Affricate consonants	A plosive followed by a fricative	Behrman (2007)
Nasal consonants	Low frequency band of energy at approximatly 250 Hz and an absence of energy near 1kHz	House & Stevens (1956)
Glide and liquid consonants	Transition of formants	Kent (1997)

TABLE 4. Relative formant position of vowels by place on spectrogram.

Vowels by Place	Relative formant position on spectrogram	Literature
High front vowels	Low F1 high F2	Disner (1986)
High back vowels	High F1 high F2	Fry (1979)
Low front vowels	High F1 low F2	Davenport & Hannahs (1998)
Low back vowels	High F1 low F2	Behrman (2007)

TABLE 5. Two-way (Consonant by jaw) RM ANOVA results for the normal-hearing group: All experimental measures for the vowels /i/, /a/, and /u/ respectively.

	N	Jaw Effect	Consonant Effect	Consonant x Jaw Interaction
/i/				
F1	54	F(1, 16) = 3.351, p = 0.105	F(2, 16) = 0.077, p = 0.927	F(2, 16) = 0.687, p = 0.517
F2	54	F(1, 16) = 3.953, p = 0.006*	F(2, 16) = 0.473, p = 0.631	F(2, 16) = 1.313, p = 0.296
F0	54	F(1, 16) = 0.280, p = 0.611	F(2, 16) = 4.169, p = 0.035*	F(2, 16) = 0.200, p = 0.821
%jitter	54	F(1, 16) = 0.022, p = 0.887	F(2, 16) = 0.706, p = 0.508	F(2, 16) = 2.001, p = 0.168
%shimmer	54	F(1, 16) = 0.052, p = 0.826	F(2, 16) = 1.457, p = 0.262	F(2, 16) = 2.692, p = 0.098
SNR	54	F(1, 16) = 2.331, p = 0.165	F(2, 16) = 4.390, p = 0.030*	F(2, 16) = 1.663, p = 0.221
V- Length	54	F(1, 16) = 10.487, p = 0.0012*	F(2, 16) = 13.508, p < 0.001**	F(2, 16) = 0.142, p = 0.869
C-Length	54	F(1, 16) = 0.106, p = 0.753	F(2, 16) =127.306, p < 0.001**	F(2, 16) = 2.472, p = 0.116
M1	54	F(1, 16) = 0.109, p = 0.750	F(2, 16) = 20.229, p < 0.001**	F(2, 16) = 1.683, p = 0.217
M2	54	F(1, 16) = 0.385, p = 0.552	F(2, 16) =205.904, p < 0.001**	F(2, 16) = 0.110, p = 0.897
OQ	54	F(1, 16) = 0.330, p = 0.581	F(2, 16) = 2.255, p < 0.137	F(2, 16) = 0.691, p = 0.515
SQ	54	F(1, 16) = 0.522, p = 0.490	F(2, 16) = 2.342, p < 0.128	F(2, 16) = 0.389, p = 0.684
Jaw-disp	54	F(1, 16) = 1.069, p = 0.331	F(2, 16) = 0.872, p < 0.437	F(2, 16) = 2.931, p = 0.082
/a/				
F1	54	F(1, 16) = 0.235, p = 0.641	F(2, 16) = 96.874, p < 0.001**	F(2, 16) = 2.072, p = 0.158
F2	54	F(1, 16) = 2.291, p = 0.169	F(2, 16) = 5.754, p = 0.013*	F(2, 16) = 0.660, p = 0.530
F0	54	F(1, 16) = 0.431, p = 0.530	F(2, 16) = 6.713, p = 0.008*	F(2, 16) = 0.165, p = 0.850
%jitter	54	F(1, 16) = 1.572, p = 0.245	F(2, 16) = 0.172, p = 0.844	F(2, 16) = 0.389, p = 0.684
%shimmer	54	F(1, 16) = 1.572, p = 0.245	F(2, 16) = 1.777, p = 0.201	F(2, 16) = 0.631, p = 0.545
SNR	54	F(1, 16) = 10.186, p = 0.013*	F(2, 16) = 3.761, p = 0.118	F(2, 16) = 0.167, p = 0.848
V- Length	54	F(1, 16) = 18.247, p = 0.003*	F(2, 16) = 53.839, p < 0.001**	F(2, 16) = 2.807, p = 0.090
C-Length	54	F(1, 16) = 2.163, p = 0.180	F(2, 16) = 28.201, p < 0.001**	F(2, 16) = 2.607, p = 0.105
M1	54	F(1, 16) = 0.282, p = 0.610	F(2, 16) = 17.026, p < 0.001**	F(2, 16) = 3.695, p = 0.048*
M2	54	F(1, 16) = 2.472, p = 0.155	F(2, 16) = 44.268, p < 0.001**	F(2, 16) = 0.749, p = 0.489
OQ	54	F(1, 16) = 1.160, p = 0.313	F(2, 16) = 3.864, p = 0.043*	F(2, 16) = 2.068, p = 0.159
SQ	54	F(1, 16) = 1.274, p = 0.292	F(2, 16) = 3.880, p = 0.042*	F(2, 16) = 1.514, p = 0.250
Jaw-disp	54	F(1, 16) = 5.719, p = 0.044*	F(2, 16) = 24.167, p < 0.001**	F(2, 16) = 3.328, p = 0.062
/u/				
F1	54	F(1, 16) = 0.352, p = 0.570	F(2, 16) = 3.027, p = 0.077	F(2, 16) = 3.926, p = 0.041*
F2	54	F(1, 16) = 0.019, p = 0.894	F(2, 16) = 0.123, p = 0.885	F(2, 16) = 0.717, p = 0.503
F0	54	F(1, 16) = 2.422, p = 0.158	F(2, 16) = 2.315, p = 0.131	F(2, 16) = 0.782, p = 0.474
%jitter	54	F(1, 16) = 0.270, p = 0.618	F(2, 16) = 6.848, p = 0.007*	F(2, 16) = 0.030 p = 0.971
%shimmer	54	F(1, 16) = 2.514, p = 0.152	F(2, 16) = 27.920, p < 0.001**	F(2, 16) = 0.334, p = 0.721
SNR	54	F(1, 16) = 1.408, p = 0.269	F(2, 16) = 17.384, p < 0.001**	F(2, 16) = 0.135, p = 0.875
V- Length	54	F(1, 16) = 33.065, p < 0.001**	F(2, 16) = 55.314, p < 0.001**	F(2, 16) = 2.179, p = 0.146
C-Length	54	F(1, 16) = 2.689, p = 0.140	F(2, 16) = 177.883, p < 0.001**	F(2, 16) = 8.510, p = 0.003*
M1	54	F(1, 16) = 0.150, p = 0.709	F(2, 16) = 5.459, p = 0.016*	F(2, 16) = 0.703, p = 0.510
M2	54	F(1, 16) = 0.576, p = 0.470	F(2, 16) = 90.600, p < 0.001**	F(2, 16) = 0.126, p = 0.882
OQ†		---		
SQ†		---		
Jaw-disp	54	F(1, 16) = 3.313, p = 0.106	F(2, 16) = 0.546, p = 0.590	F(2, 16) = 0.163, p = 0.851

* Significant at 0.05 level
**Significant at 0.001 level
†Missing data

TABLE 6. Two-way (consonant by jaw) ANOVA results for HI participants (H1F1, H1F2, and H1M1): Frequencies of Formant one (F1) and two (F2) and fundimental frequency (F0) for /i/, /a/, and /u/ respectively.

N		Jaw Effect	Consonant Effect	Consonant x Jaw Interaction
F1				
/i/				
HIF1	30	F(1, 24) = 1.621, p = 0.215	F(2, 24) = 3.654, p = 0.041*	F(2, 24) = 4.097, p = 0.029*
HIF2	30	F(1, 24) = 1.678, p = 0.207	F(2, 24) = 7.879, p = 0.002*	F(2, 24) = 0.022, p = 0.978
HIM1	30	F(1, 24) = 14.319, p = 0.001*	F(2, 24) = 40.147, p < 0.001**	F(2, 24) = 0.334, p = 0.719
/a/				
HIF1	29†	F(1, 23) = 4.715, p = 0.040*	F(2, 23) = 17.685, p < 0.001*	F(2, 23) = 4.398, p = 0.024*
HIF2	30	F(1, 24) = 21.214, p < 0.001**	F(2, 24) = 90.604, p < 0.001**	F(2, 24) = 3.926, p = 0.033*
HIM1	30	F(1, 24) = 3.965, p = 0.058	F(2, 24) = 33.888, p < 0.001**	F(2, 24) = 0.460, p = 0.637
/u/				
HIF1	30	F(1, 24) = 0.275, p = 0.605	F(2, 24) = 2.679, p = 0.089	F(2, 24) = 2.315, p = 0.120
HIF2	30	F(1, 24) = 10.688, p = 0.003*	F(2, 24) = 8.832, p = 0.001*	F(2, 24) = 0.420, p = 0.662
HIM1	30	F(1, 24) = 7.705, p = 0.011*	F(2, 24) = 13.348, p < 0.001**	F(2, 24) = 0.384, p = 0.685
F2				
/i/				
HIF1	30	F(1, 24) = 0.247, p = 0.624	F(2, 24) = 3.818, p = 0.036*	F(2, 24) = 0.236, p = 0.792
HIF2	30	F(1, 24) = 2.284, p = 0.144	F(2, 24) = 3.713, p = 0.039*	F(2, 24) = 0.253, p = 0.779
HIM1	30	F(1, 24) = 24.484, p < 0.001**	F(2, 24) = 39.525, p < 0.001**	F(2, 24) = 1.308, p = 0.289
/a/				
HIF1	29†	F(1, 23) = 0.011, p = 0.917	F(2, 23) = 6.871, p = 0.005*	F(2, 23) = 2.183, p = 0.135
HIF2	30	F(1, 24) = 8.945, p = 0.006*	F(2, 24) = 35.117, p < 0.001**	F(2, 24) = 4.642, p = 0.020*
HIM1	30	F(1, 24) = 0.303, p = 0.587	F(2, 24) = 138.51, p < 0.001**	F(2, 24) = 4.978, p = 0.016*
/u/				
HIF1	30	F(1, 24) = 0.005, p = 0.946	F(2, 24) = 0.289, p = 0.752	F(2, 24) = 0.537, p = 0.591
HIF2	30	F(1, 24) = 1.938, p = 0.177	F(2, 24) = 0.709, p = 0.502	F(2, 24) = 1.010, p = 0.379
HIM1	30	F(1, 24) = 2.678, p = 0.115	F(2, 24) = 8.749, p = 0.001*	F(2, 24) = 3.237, p = 0.057
F0				
/i/				
HIF1	30	F(1, 24) = 8.818, p = 0.007*	F(2, 24) = 2.78, p = 0.082	F(2, 24) = 3.733, p = 0.039*
HIF2	30	F(1, 24) = 2.815, p = 0.106	F(2, 24) = 11.54, p < 0.001**	F(2, 24) = 0.536, p = 0.592
HIM1	30	F(1, 24) = 0.173, p = 0.681	F(2, 24) = 1.64, p = 0.215	F(2, 24) = 1.919, p = 0.169
/a/				
HIF1	29†	F(1, 23) = 0.377, p = 0.545	F(2, 23) = 3.909, p = 0.035*	F(2, 23) = 0.869, p = 0.433
HIF2	30	F(1, 24) = 8.551, p = 0.007*	F(2, 24) = 25.114, p < 0.001**	F(2, 24) = 0.064, p = 0.938
HIM1	30	F(1, 24) = 0.401, p = 0.533	F(2, 24) = 3.551, p = 0.045*	F(2, 24) = 0.088, p = 0.916
/u/				
HIF1	30	F(1, 24) = 3.035, p = 0.094	F(2, 24) = 0.680, p = 0.516	F(2, 24) = 0.723, p = 0.496
HIF2	30	F(1, 24) = 9.047, p = 0.006*	F(2, 24) = 3.337, p = 0.053	F(2, 24) = 3.016, p = 0.068
HIM1	30	F(1, 24) = 0.060, p = 0.809	F(2, 24) = 3.467, p = 0.048*	F(2, 24) = 1.300, p = 0.291

* Significant at 0.05 level
**Significant at 0.001 level
†Missing data

TABLE 7. Two-way (consonant by jaw) ANOVA results for HI participants (H1F1, H1F2, and H1M1): Percent jitter, percent shimmer, and signal to noise ratio (SNR) for /i/, /a/, and /u/ respectively.

	N	Jaw Effect	Consonant Effect	Consonant x Jaw Interaction
Percent jitter				
/i/				
HIF1	30	F(1, 24) = 0.653, p = 0.427	F(2, 24) = 6.136, p = 0.007*	F(2, 24) = 0.989, p = 0.387
HIF2	30	F(1, 24) = 2.726, p = 0.112	F(2, 24) = 7.438, p = 0.003*	F(2, 24) = 2.980, p = 0.070
HIM1	30	F(1, 24) = 1.488, p = 0.234	F(2, 24) = 7.791, p = 0.002*	F(2, 24) = 2.701, p = 0.088
/a/				
HIF1	29†	F(1, 23) = 0.1440, p = 0.708	F(2, 23) = 0.511, p = 0.607	F(2, 23) = 0.138, p = 0.872
HIF2	30	F(1, 24) = 0.0695, p = 0.794	F(2, 24) = 3.753, p = 0.038*	F(2, 24) = 0.246, p = 0.784
HIM1	30	F(1, 24) = 0.0154, p = 0.902	F(2, 24) = 4.149, p = 0.028*	F(2, 24) = 1.546, p = 0.234
/u/				
HIF1	30	F(1, 24) = 0.220, p = 0.643	F(2, 24) = 3.364, p = 0.052	F(2, 24) = 3.878, p = 0.035*
HIF2	30	F(1, 24) = 4.735, p = 0.040*	F(2, 24) = 7.516, p = 0.003*	F(2, 24) = 0.351, p = 0.708
HIM1	30	F(1, 24) = 2.746, p = 0.111	F(2, 24) = 6.177, p = 0.007*	F(2, 24) = 0.580, p = 0.568
Percent shimmer				
/i/				
HIF1	30	F(1, 24) = 0.223, p = 0.641	F(2, 24) = 7.983, p = 0.002*	F(2, 24) = 0.120, p = 0.887
HIF2	30	F(1, 24) = 0.711, p = 0.407	F(2, 24) = 51.106, p < 0.001**	F(2, 24) = 1.843, p = 0.181
HIM1	29†	F(1, 23) = 17.846, p < 0.001**	F(2, 23) = 29.361, p < 0.001**	F(2, 23) = 3.800, p = 0.037*
/a/				
HIF1	29†	F(1, 23) = 1.795, p = 0.193	F(2, 23) = 0.634, p = 0.539	F(2, 23) = 0.633, p = 0.540
HIF2	30	F(1, 24) = 1.547, p = 0.226	F(2, 24) = 3.774, p = 0.038*	F(2, 24) = 2.693, p = 0.088
HIM1	30	F(1, 24) = 3.037, p = 0.094	F(2, 24) = 8.628, p = 0.002*	F(2, 24) = 0.989, p = 0.387
/u/				
HIF1	30	F(1, 24) = 2.673, p = 0.115	F(2, 24) = 22.673, p < 0.001**	F(2, 24) = 2.907, p = 0.074
HIF2	30	F(1, 24) = 4.427, p = 0.046*	F(2, 24) = 15.495, p < 0.001**	F(2, 24) = 0.098, p = 0.907
HIM1	30	F(1, 24) = 7.455, p = 0.012*	F(2, 24) = 30.691, p < 0.001**	F(2, 24) = 0.796, p = 0.463
SNR				
/i/				
HIF1	30	F(1, 24) = 0.084, p = 0.775	F(2, 24) = 1.301, p = 0.291	F(2, 24) = 0.349, p = 0.709
HIF2	30	F(1, 24) = 8.838, p = 0.007*	F(2, 24) = 28.245, p < 0.001**	F(2, 24) = 2.108, p = 0.143
HIM1	30	F(1, 24) = 1.210, p = 0.282	F(2, 24) = 12.828, p < 0.001**	F(2, 24) = 1.507, p = 0.242
/a/				
HIF1	29†	F(1, 23) = 0.778, p = 0.387	F(2, 23) = 3.349, p = 0.053	F(2, 23) = 1.544, p = 0.235
HIF2	30	F(1, 24) = 0.810, p = 0.377	F(2, 24) = 12.961, p < 0.001**	F(2, 24) = 2.261, p = 0.126
HIM1	30	F(1, 24) = 7.353, p = 0.012*	F(2, 24) = 13.397, p < 0.001**	F(2, 24) = 0.336, p = 0.718
/u/				
HIF1	30	F(1, 24) = 7.234, p = 0.013*	F(2, 24) = 24.854, p < 0.001**	F(2, 24) = 1.126, p = 0.341
HIF2	30	F(1, 24) = 9.861, p = 0.004*	F(2, 24) = 20.869, p < 0.001**	F(2, 24) = 0.184, p = 0.833
HIM1	30	F(1, 24) = 8.356, p = 0.008*	F(2, 24) = 2.840, p = 0.078	F(2, 24) = 3.267, p = 0.056

* Significant at 0.05 level
**Significant at 0.001 level
†Missing data

TABLE 8. Two-way (Consonant by jaw) ANOVA results for HI participants (H1F1, H1F2, and H1M1): Vowel length and consonant length for /i/, /a/, and /u/ respectively.

	N	Jaw Effect	Consonant Effect	Consonant x Jaw Interaction
Vowel length				
/i/				
HIF1	30	F(1, 24) = 8.747, p = 0.007*	F(2, 24) = 43.676, p < 0.001**	F(2, 24) = 0.022, p = 0.979
HIF2	30	F(1, 24) = 0.599, p = 0.447	F(2, 24) = 75.139, p < 0.001**	F(2, 24) = 2.623, p = 0.093
HIM1	30	F(1, 24) = 2.964, p = 0.098	F(2, 24) = 108.46, p < 0.001**	F(2, 24) = 3.954, p = 0.033*
/a/				
HIF1	29†	F(1, 23) = 61.170, p < 0.001**	F(2, 23) = 80.785, p < 0.001**	F(2, 23) = 0.096, p = 0.908
HIF2	30	F(1, 24) = 1.212, p = 0.282	F(2, 24) = 244.435, p < 0.001**	F(2, 24) = 0.515, p = 0.604
HIM1	30	F(1, 24) = 4.455, p = 0.045*	F(2, 24) = 95.749, p < 0.001**	F(2, 24) = 1.764, p = 0.193
/u/				
HIF1	30	F(1, 24) = 0.610, p = 0.442	F(2, 24) = 51.865, p < 0.001**	F(2, 24) = 2.536, p = 0.100
HIF2	30	F(1, 24) = 0.142, p = 0.709	F(2, 24) = 57.820, p < 0.001**	F(2, 24) = 1.906, p = 0.171
HIM1	30	F(1, 24) = 0.049, p = 0.827	F(2, 24) = 109.697, p < 0.001**	F(2, 24) = 0.377, p = 0.690
Consonant length				
/i/				
HIF1	30	F(1, 24) = 3.321, p = 0.081	F(2, 24) = 32.085, p < 0.001**	F(2, 24) = 2.611, p = 0.094
HIF2	30	F(1, 24) = 6.620, p = 0.017*	F(2, 24) = 16651.74, p < 0.001**	F(2, 24) = 4.478, p = 0.022*
HIM1	30	F(1, 24) = 0.104, p = 0.750	F(2, 24) = 148.66, p < 0.001**	F(2, 24) = 0.232, p = 0.795
/a/				
HIF1	29†	F(1, 23) = 2.584, p = 0.122	F(2, 23) = 112.093, p < 0.001**	F(2, 23) = 1.485, p = 0.247
HIF2	30	F(1, 24) = 1.135, p = 0.297	F(2, 24) = 179.356, p < 0.001**	F(2, 24) = 1.142, p = 0.336
HIM1	30	F(1, 24) = 0.428, p = 0.519	F(2, 24) = 739.948, p < 0.001**	F(2, 24) = 0.733, p = 0.491
/u/				
HIF1	30	F(1, 24) = 0.005, p = 0.947	F(2, 24) = 314.963, p < 0.001**	F(2, 24) = 0.296, p = 0.746
HIF2	30	F(1, 24) = 4.697, p = 0.040*	F(2, 24) = 79.521, p < 0.001**	F(2, 24) = 3.598, p = 0.043*
HIM1	30	F(1, 24) = 0.063, p = 0.804	F(2, 24) = 740.380, p < 0.001**	F(2, 24) = 1.089, p = 0.353

* Significant at 0.05 level
**Significant at 0.001 level
†Missing data

Table 9. Two-way (Consonant by jaw) ANOVA results for HI participants (H1F1, H1F2, and H1M1): Spectral moments one (M1) and two (M2) averaged over all consonants for /i/, /a/, and /u/ respectively.

	N	Jaw Effect	Consonant Effect	Consonant x Jaw Interaction
M1				
/i/				
HIF1	30	F(1, 24) = 3.326, p = 0.081	F(2, 24) = 19.952, p < 0.001**	F(2, 24) = 0.420, p = 0.662
HIF2	30	F(1, 24) = 1.932, p = 0.177	F(2, 24) = 15.644, p < 0.001**	F(2, 24) = 0.091, p = 0.913
HIM1	30	F(1, 24) = 3.283, p = 0.083	F(2, 24) = 6.605, p = 0.005*	F(2, 24) = 0.553, p = 0.583
/a/				
HIF1	29†	F(1, 23) = 0.692, p = 0.414	F(2, 23) = 29.089, p < 0.001**	F(2, 23) = 0.578, p = 0.569
HIF2	30	F(1, 24) = 10.618, p = 0.003*	F(2, 24) = 62.448, p < 0.001**	F(2, 24) = 2.701, p = 0.088
HIM1	30	F(1, 24) = 0.170, p = 0.684	F(2, 24) = 5.597, p = 0.010*	F(2, 24) = 0.386, p = 0.684
/u/				
HIF1	30	F(1, 24) = 1.075, p = 0.310	F(2, 24) = 30.941, p < 0.001**	F(2, 24) = 4.487, p = 0.022*
HIF2	30	F(1, 24) = 5.340, p = 0.030*	F(2, 24) = 10.762, p < 0.001**	F(2, 24) = 0.557, p = 0.580
HIM1	30	F(1, 24) = 5.321, p = 0.030*	F(2, 24) = 2.995, p = 0.069	F(2, 24) = 0.952, p = 0.400
M2				
/i/				
HIF1	29†	F(1, 23) = 0.195, p = 0.663	F(2, 23) = 11.216, p < 0.001**	F(2, 23) = 0.278, p = 0.760
HIF2	30	F(1, 24) = 0.123, p = 0.728	F(2, 24) = 41.347, p < 0.001**	F(2, 24) = 0.449, p = 0.643
HIM1	30	F(1, 24) = 2.504, p = 0.127	F(2, 24) = 60.361, p < 0.001**	F(2, 24) = 6.487, p = 0.006*
/a/				
HIF1	29†	F(1, 23) = 0.1420, p = 0.710	F(2, 23) = 10.213, p < 0.001**	F(2, 23) = 0.444, p = 0.647
HIF2	30	F(1, 24) = 0.0287, p = 0.867	F(2, 24) = 119.370, p < 0.001**	F(2, 24)= 11.615, p < 0.001**
HIM1	30	F(1, 24) = 0.0194, p = 0.890	F(2, 24) = 23.675, p < 0.001**	F(2, 24) = 0.201, p = 0.819
/u/				
HIF1	30	F(1, 24) = 5.898, p = 0.023*	F(2, 24) = 25.673, p < 0.001**	F(2, 24) = 1.416, p = 0.262
HIF2	30	F(1, 24) = 0.988, p = 0.330	F(2, 24) = 56.068, p < 0.001**	F(2, 24) = 0.673, p = 0.520
HIM1	30	F(1, 24) = 0.308, p = 0.584	F(2, 24) = 36.123, p < 0.001**	F(2, 24) = 2.415, p = 0.111

*Significant at 0.05 level
**Significant at 0.001 level
†Missing data

TABLE 10. Two-way (consonant by jaw) ANOVA results for HI participants (H1F1, H1F2, and H1M1): Jaw displacement for /i/, /a/, and /u/ respectively.

	N	Jaw Effect	Consonant Effect	Consonant x Jaw Interaction
Jaw displacement				
/i/				
HIF1	30	F(1, 24) = 0.992, p = 0.329	F(2, 24) = 1.528, p = 0.237	F(2, 24) = 2.415, p = 0.111
HIF2	30	F(1, 24) = 22.839, p < 0.001**	F(2, 24) = 5.854, p = 0.008*	F(2, 24) = 0.553, p = 0.582
HIM1	30	F(1, 24) = 2.404, p = 0.134	F(2, 24) = 0.849, p = 0.440	F(2, 24) = 4.155, p = 0.028*
/a/				
HIF2	28†	F(1, 22) = 10.221, p = 0.004*	F(2, 22) = 15.30, p < 0.001**	F(2, 22) = 2.434, p = 0.111
HIF2	26†	F(1, 20) = 5.597, p = 0.028*	F(2, 20) = 4.015, p = 0.034*	F(2, 20) = 5.769, p = 0.011*
HIM1	29†	F(1, 23) = 26.398, p < 0.001**	F(2, 23) = 15.980, p < 0.001**	F(2, 23) = 0.133, p = 0.876
/u/				
HIF1	22†	F(1, 16) = 0.035, p = 0.854	F(2, 16) = 1.288, p = 0.303	F(2, 16) = 0.370, p = 0.697
HIF2	28†	F(1, 22) = 4.497, p = 0.045*	F(2, 22) = 0.925, p = 0.411	F(2, 22) = 2.250, p = 0.129
HIM1	29†	F(1, 23) = 5.735, p = 0.025*	F(2, 23) = 0.692, p = 0.511	F(2, 23) = 3.884, p = 0.035*

*Significant at 0.05 level
**Significant at 0.001 level
†Missing data

Fig 1.1 Average vowel plots for the normal-hearing group

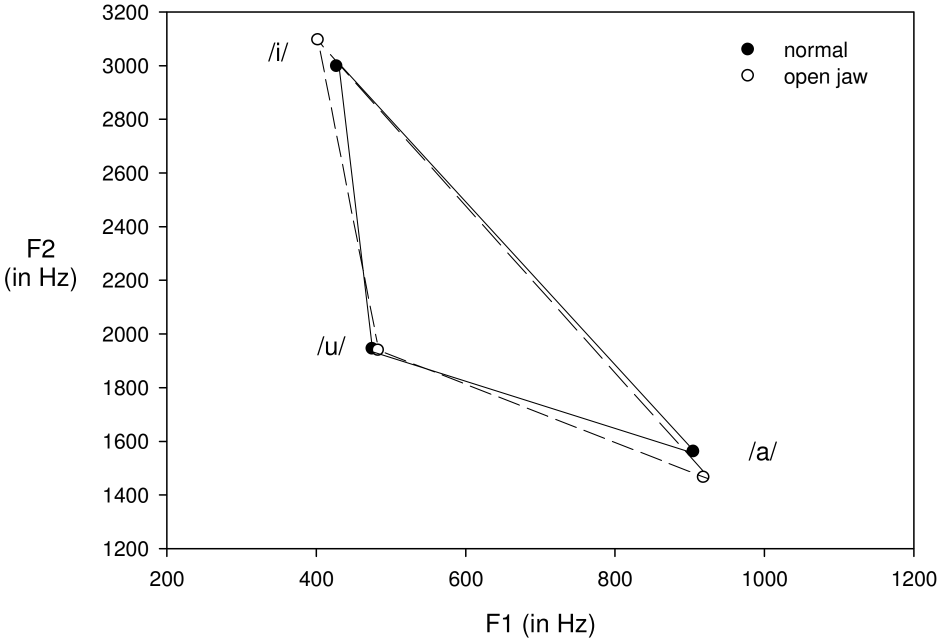


Fig. 1.2 Vowel plots for the male and female normal-hearing groups separately

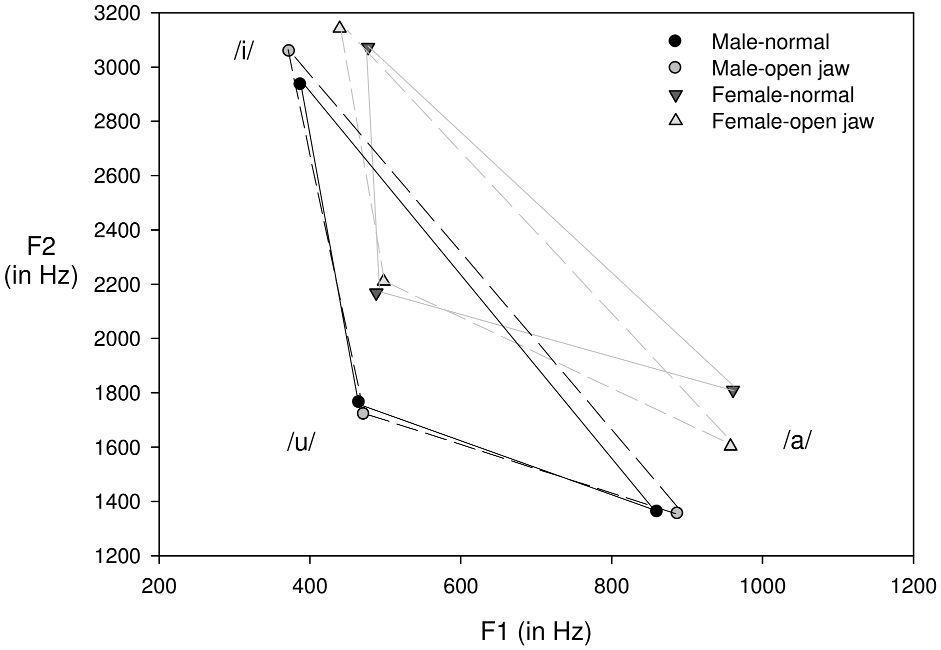


Figure 1. The average vowel plots of /i/, /a/, and /u/ for the normal-hearing group as a whole (Fig. 2.1) and for the male and female normal-hearing groups separately (Fig. 2.2).

Fig 2.1 Average vowel plots for the hearing-impaired group

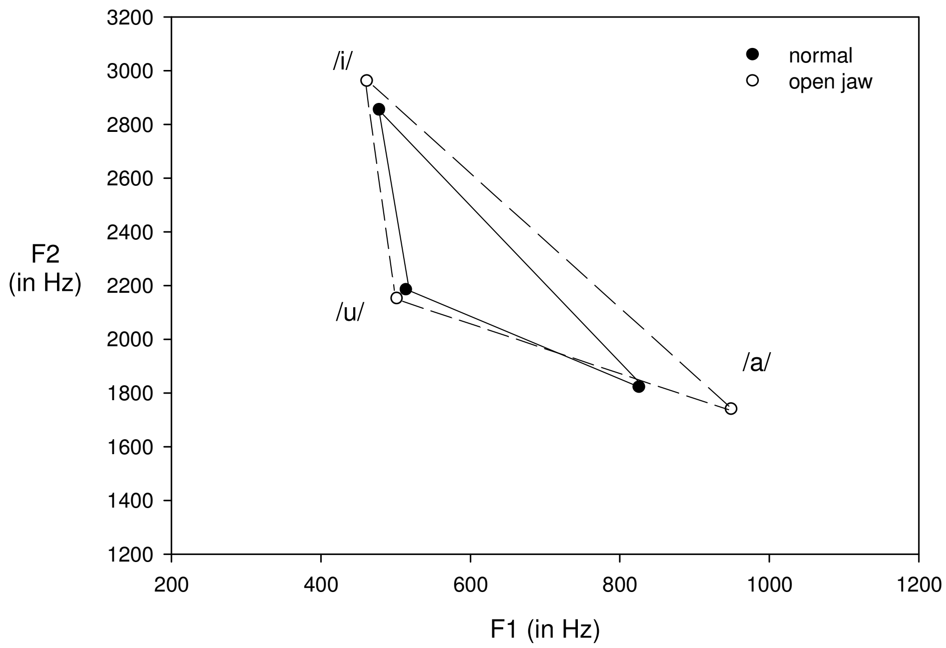


Fig 2.2 Vowel plots for individuals in the hearing-impaired group

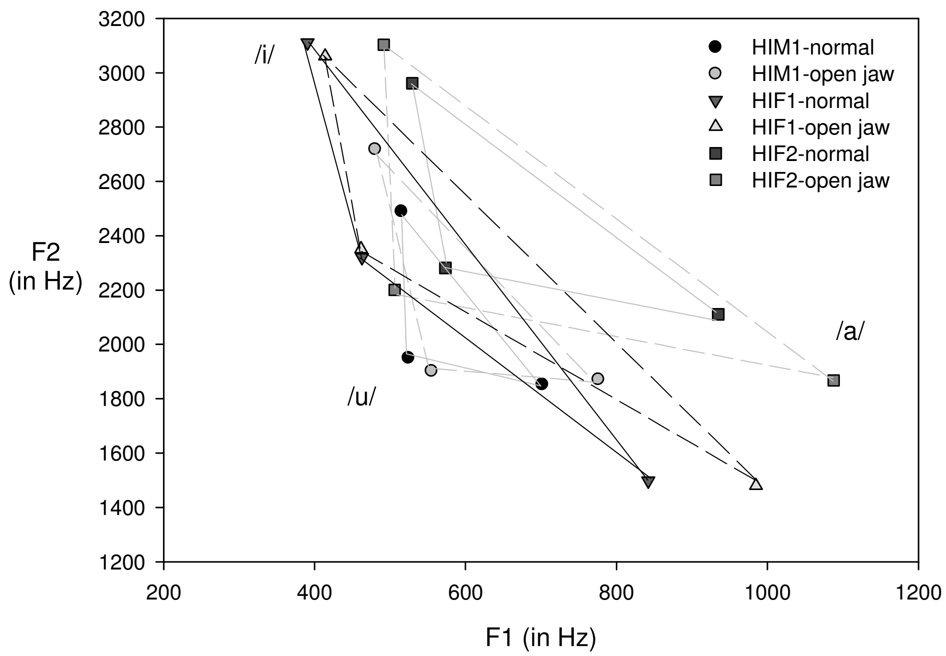


Figure 2. The average vowel plots of /i/, /a/, and /u/ for the hearing-impaired group as a whole (Fig. 2.1) and for the three individuals (H1F1, H1F2, and H1M1) in the hearing-impaired group separately (Fig. 2.2).

Figure 3.1: Vowel /i/

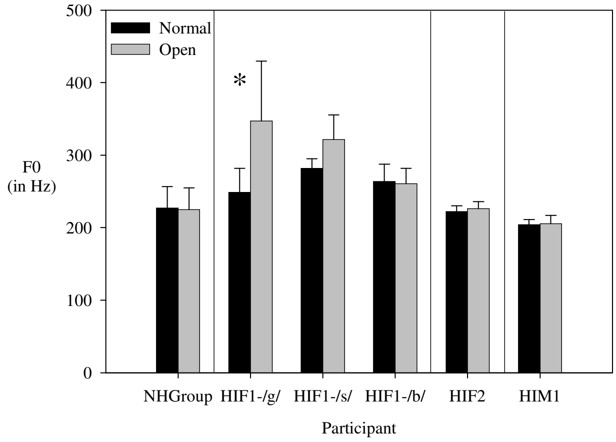


Figure 3.2: Vowel /a/

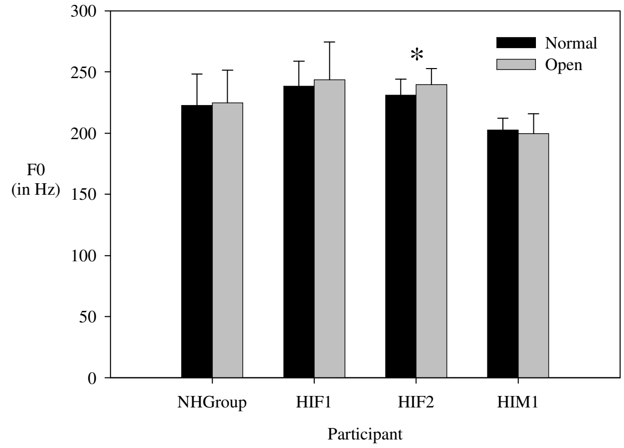


Figure 3.3: Vowel /u/

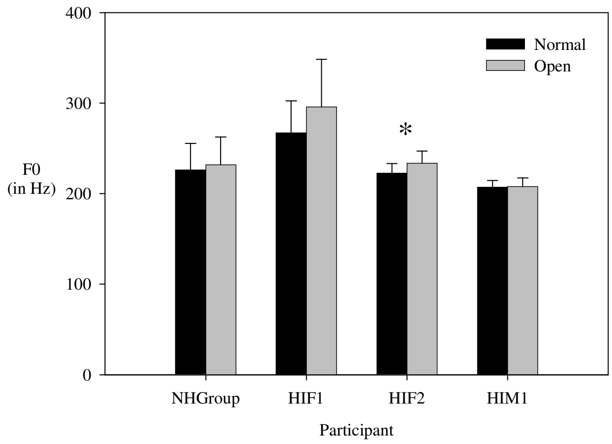


Figure 3. Jaw effect on fundamental frequency (F0). Means and standard deviations of F0 for each of the vowels /i, a, u/ in the normal and open jaw conditions for the normal-hearing group (NHGroup) and the three hearing-impaired participants (HIF1, HIF2, HIM1). Data showing a significant consonant and jaw interaction effect were presented in the three consonant (/g, s, b/) contexts separately. Significantly different pairs in each data set were marked with an asterisk ("*").

Figure 4.1: Vowel /i/

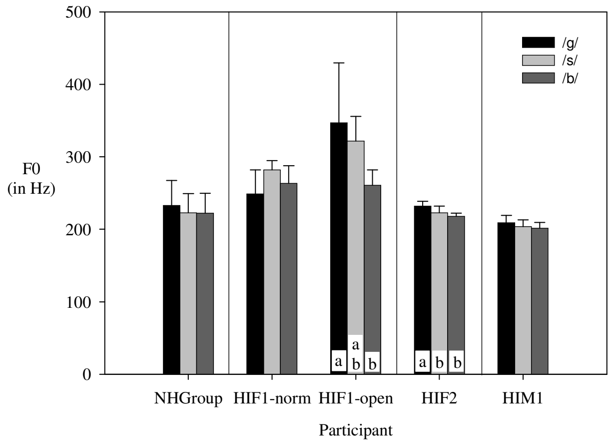


Figure 4.2: Vowel /a/

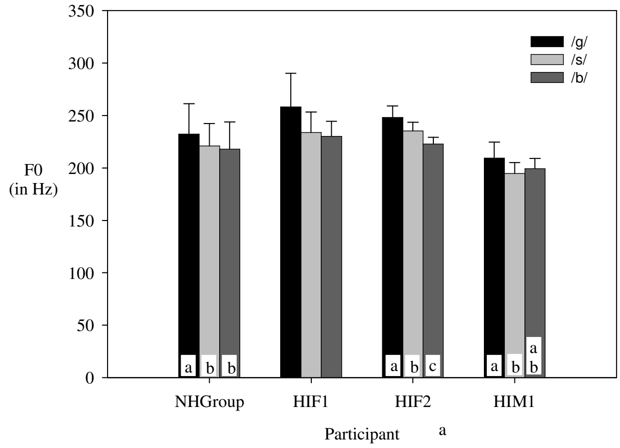


Figure 4.3: Vowel /u/

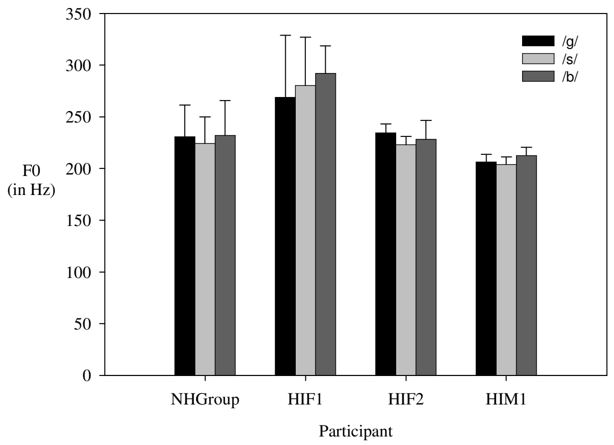


Figure 4. Consonant effect on fundamental frequency (F0). Means and standard deviations of F0 for each of the vowels /i, a, u/ in the three consonant (/g, s, b/) contexts for the normal-hearing group (NHGroup) and the three hearing-impaired participants (HIF1, HIF2, HIM1). Data showing a significant consonant and jaw interaction effect were presented in the normal ("norm") and open jaw conditions separately. Significantly different pairs in each data set were marked with different letters.

Figure 5.1: Vowel /i/

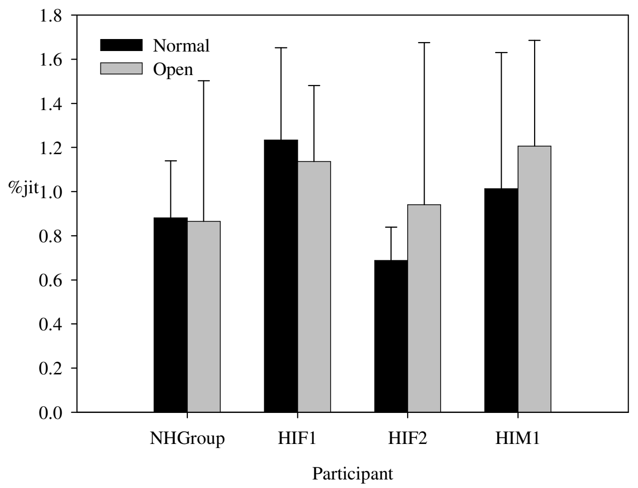


Figure 5.2: Vowel /a/

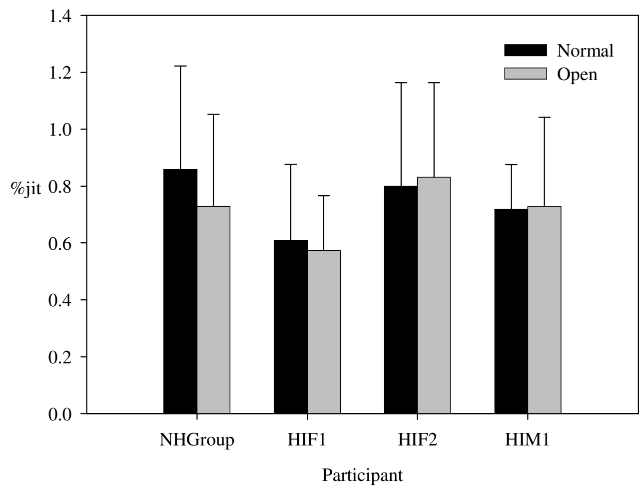


Figure 5.3: Vowel /u/

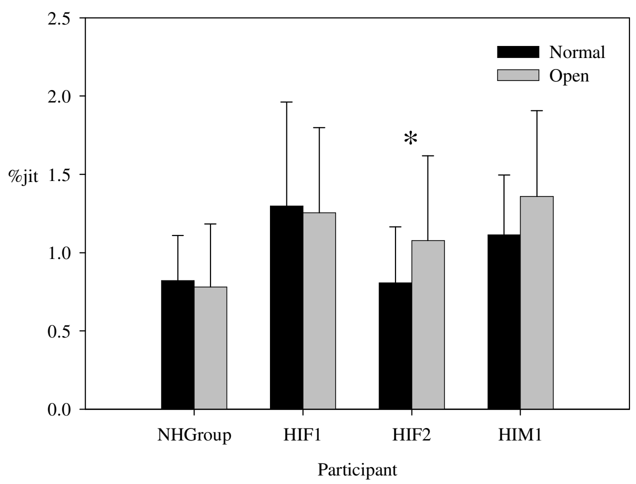


Figure 5. Jaw effect on percent jitter (%jit). Means and standard deviations of %jit for each of the vowels /i, a, u/ in the normal and open jaw conditions for the normal-hearing group (NHGroup) and the three hearing-impaired participants (HIF1, HIF2, HIM1). Significantly different pairs in each data set were marked with an asterisk ("*").

Figure 6.1: Vowel /i/

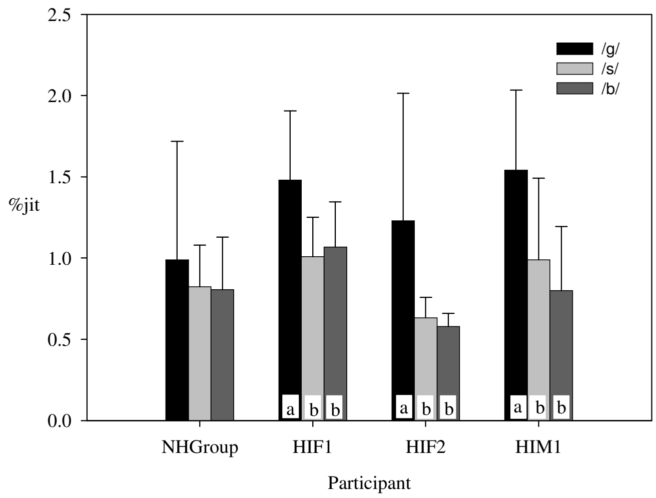


Figure 6.2: Vowel /a/

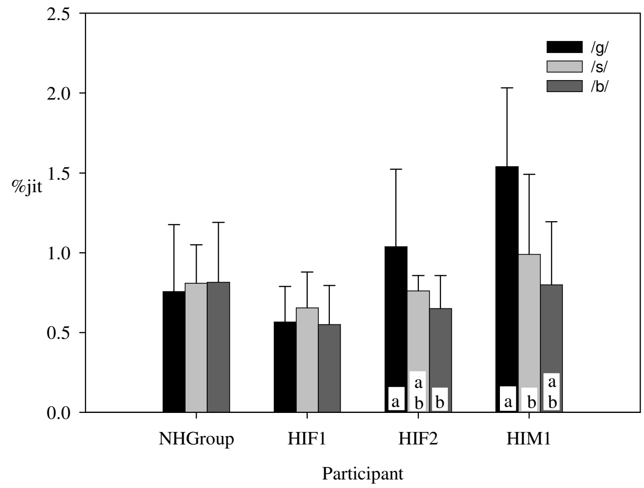


Figure 6.3: Vowel /u/

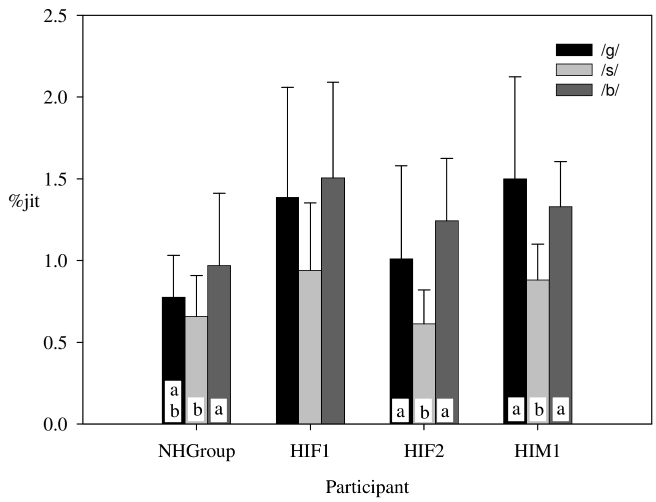


Figure 6. Consonant effect on percent jitter (%jit). Means and standard deviations of %jit for each of the vowels /i, a, u/ in the three consonant (/g, s, b/) contexts for the normal-hearing group (NHGroup) and the three hearing-impaired participants (HIF1, HIF2, HIM1). Significantly different pairs in each data set were marked with different letters.

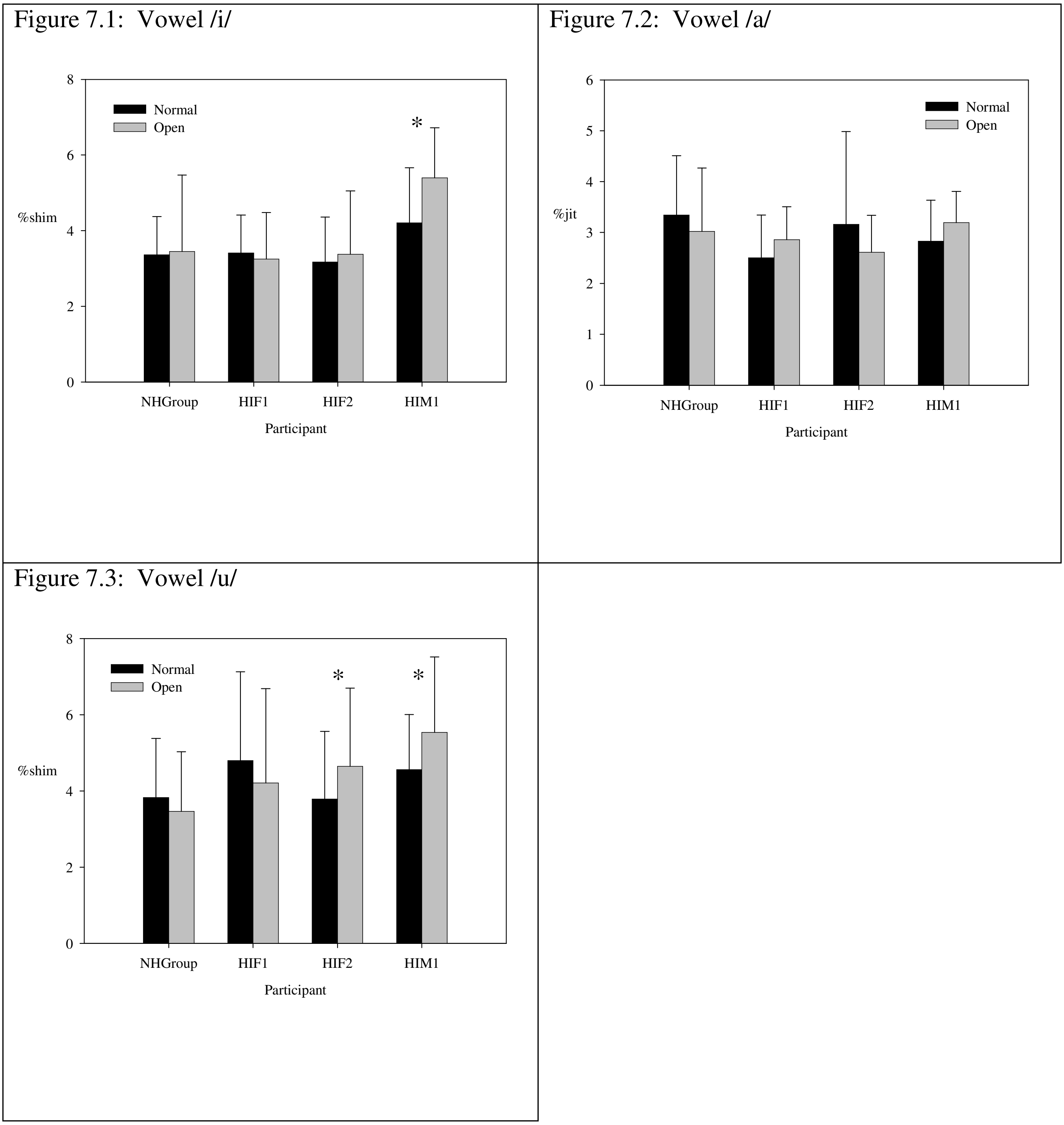


Figure 7. Jaw effect on percent shimmer (%shim). Means and standard deviations of %shim for each of the vowels /i, a, u/ in the normal and open jaw conditions for the normal-hearing group (NHGroup) and the three hearing-impaired participants . Significantly different pairs in each data set were marked with an asterisk ("*").

Figure 8.1: Vowel /i/

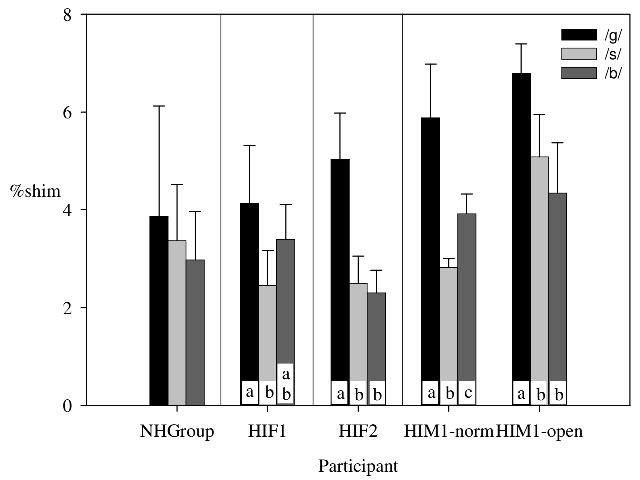


Figure 8.2: Vowel /a/

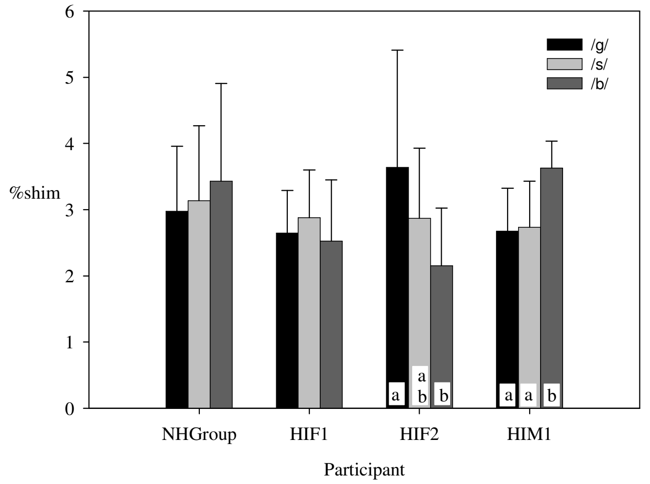


Figure 8.3: Vowel /u/

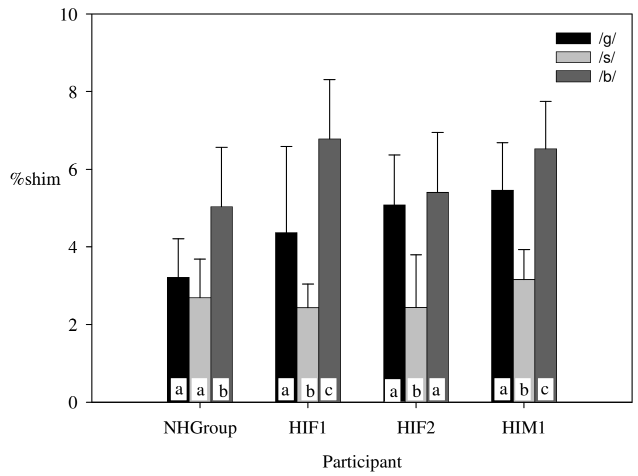


Figure 8. Consonant effect on percent shimmer (%shim). Means and standard deviations of %shim for each of the vowels /i, a, u/ in the three consonant (/g, s, b/) contexts for the normal-hearing group (NHGroup) and the three hearing-impaired participants (HIF1, HIF2, HIM1). Data showing a significant consonant and jaw interaction effect were presented in the normal ("norm") and open jaw conditions separately. Significantly different pairs in each data set were marked with different letters.

Figure 9.1: Vowel /i/

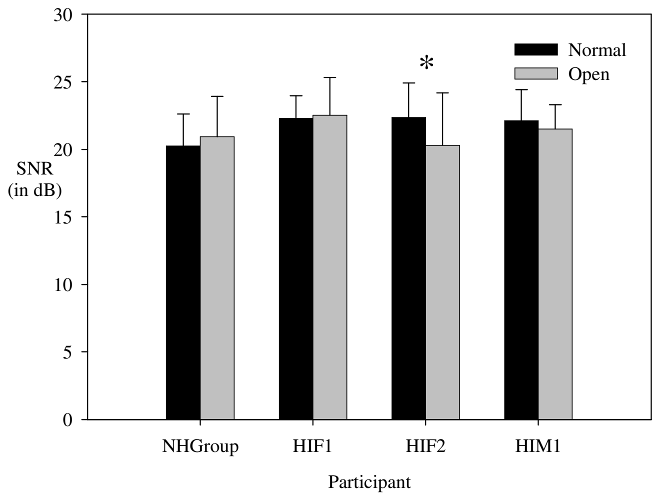


Figure 9.2: Vowel /a/

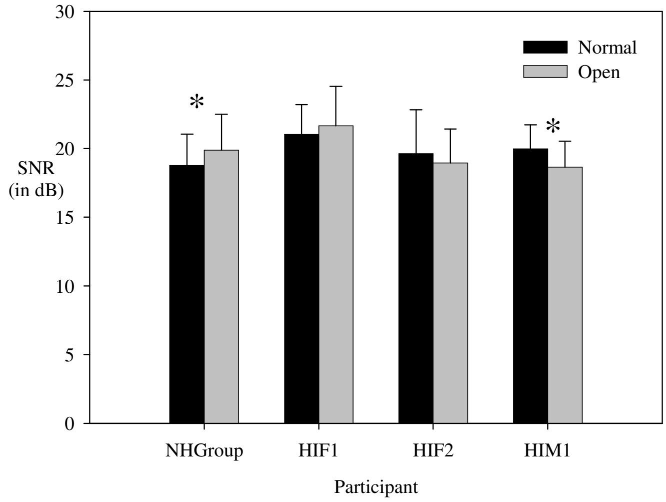


Figure 9.3: Vowel /u/

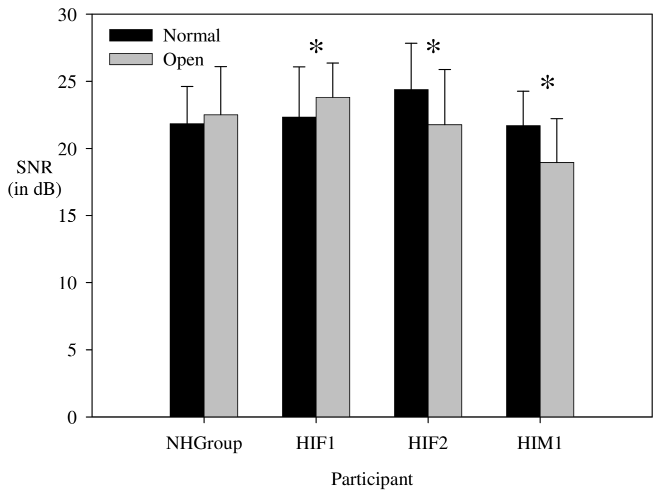


Figure 9. Jaw effect on signal-to-noise ratio (SNR). Means and standard deviations of SNR for each of the vowels /i, a, u/ in the normal and open jaw conditions for the normal-hearing group (NHGroup) and the three hearing-impaired participants (HIF1, HIF2, HIM1). Significantly different pairs in each data set were marked with an asterisk ("*").

Figure 10.1: Vowel /i/

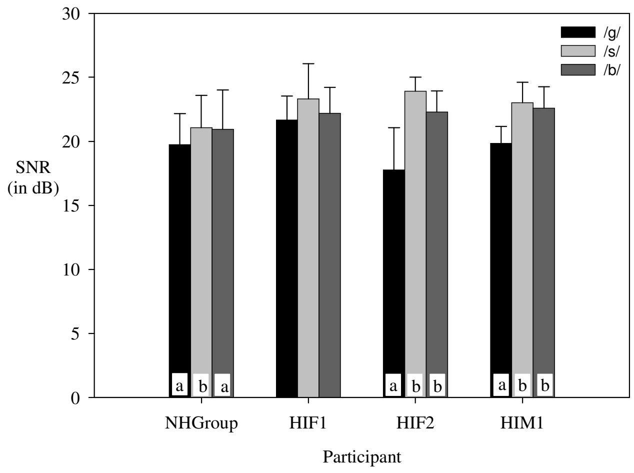


Figure 10.2: Vowel /a/

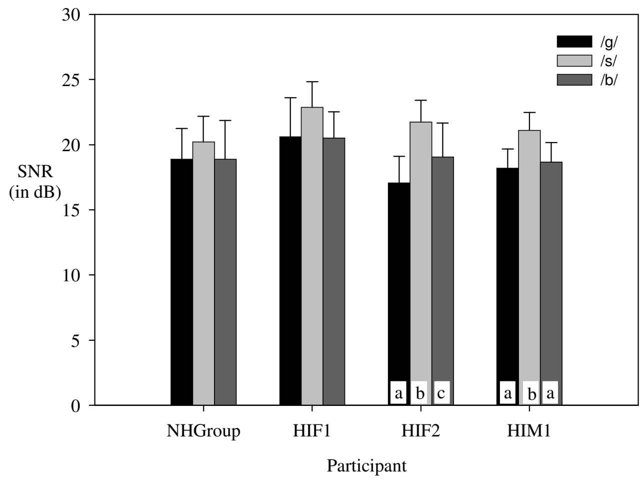


Figure 10.3: Vowel /u/

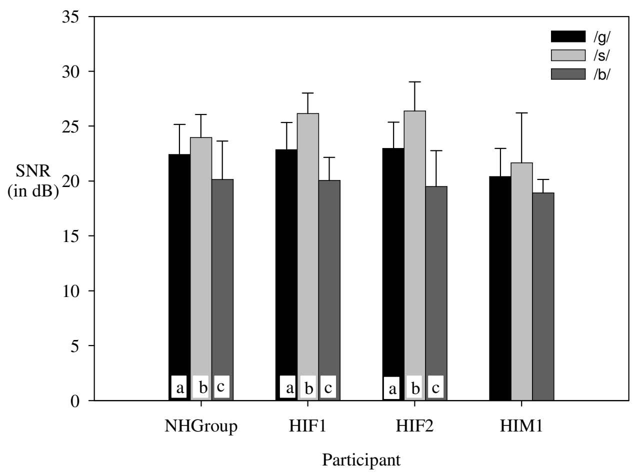


Figure 10. Consonant effect on signal-to-noise ratio (SNR). Means and standard deviations of SNR for each of the vowels /i, a, u/ in the three consonant (/g, s, b/) contexts for the normal-hearing group (NHGroup) and the three hearing-impaired participants (HIF1, HIF2, HIM1). Significantly different pairs in each data set were marked with different letters.

Figure 11.1: Vowel /i/

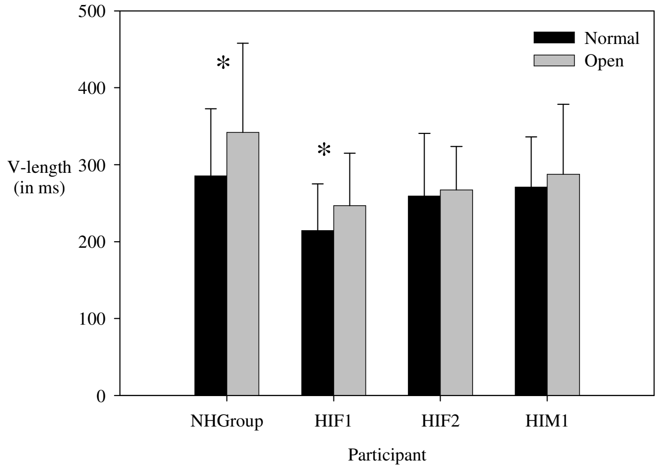


Figure 11.2: Vowel /a/

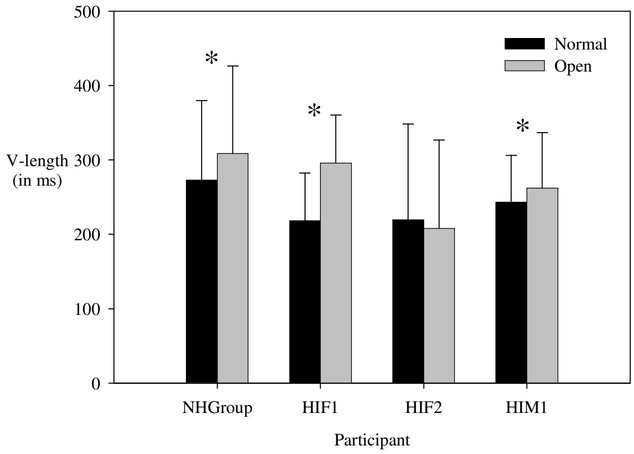


Figure 11.3: Vowel /u/

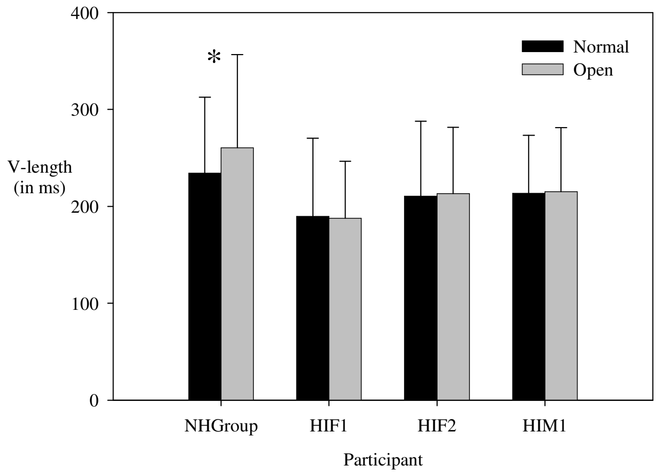


Figure 11. Jaw effect on vowel length (V-length). Means and standard deviations of V-length for each of the vowels /i, a, u/ in the normal and open jaw conditions for the normal-hearing group (NHGroup) and the three hearing-impaired participants (HIF1, HIF2, HIM1). Significantly different pairs in each data set were marked with an asterisk ("*").

Figure 12.1: Vowel /i/

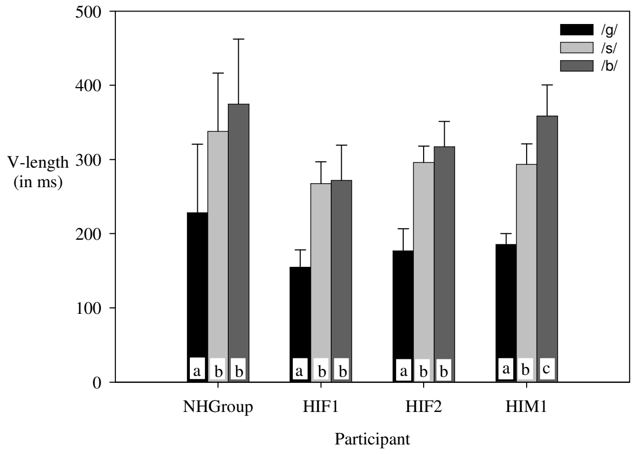


Figure 12.2: Vowel /a/

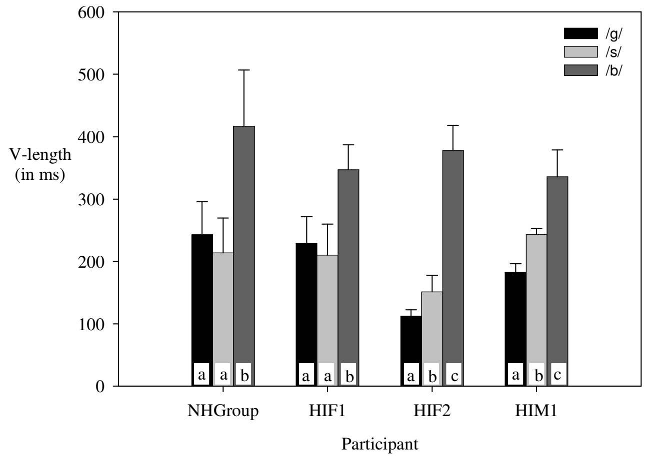


Figure 12.3: Vowel /u/

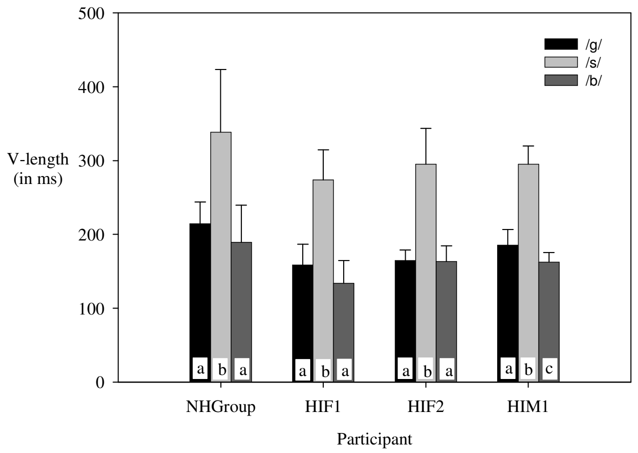


Figure 12.. Consonant effect on vowel length (V-length). Means and standard deviations of V-length for each of the vowels /i, a, u/ in the three consonant (/g, s, b/) contexts for the normal-hearing group (NHGroup) and the three hearing-impaired participants (HIF1, HIF2, HIM1). Data showing a significant consonant and jaw interaction effect were presented in the normal ("norm") and open jaw conditions separately. Significantly different pairs in each data set were marked with different letters.

Figure 13.1: Vowel /i/

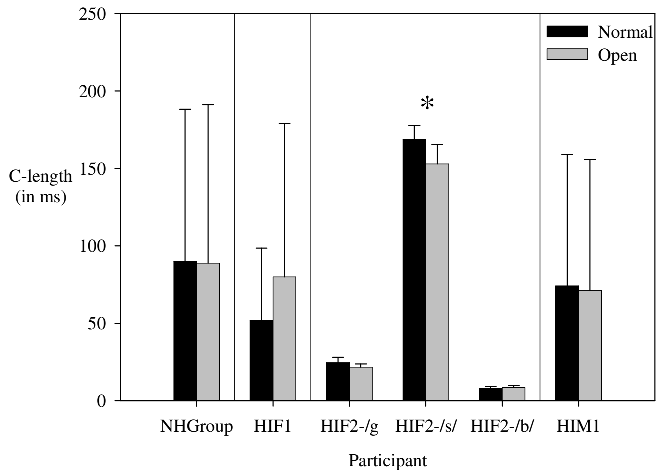


Figure 13.2: Vowel /a/

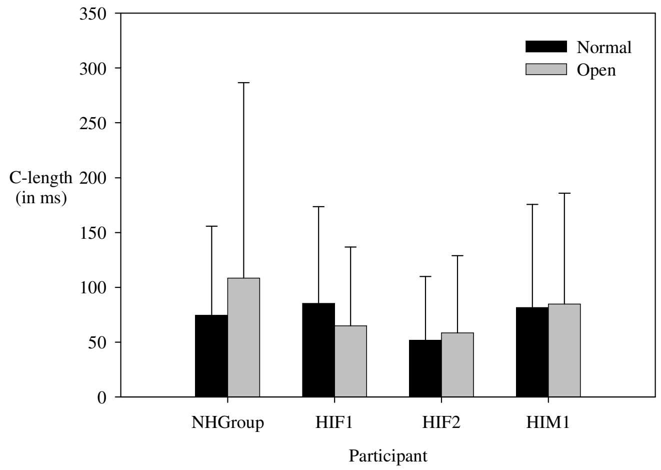


Figure 13.3: Vowel /u/

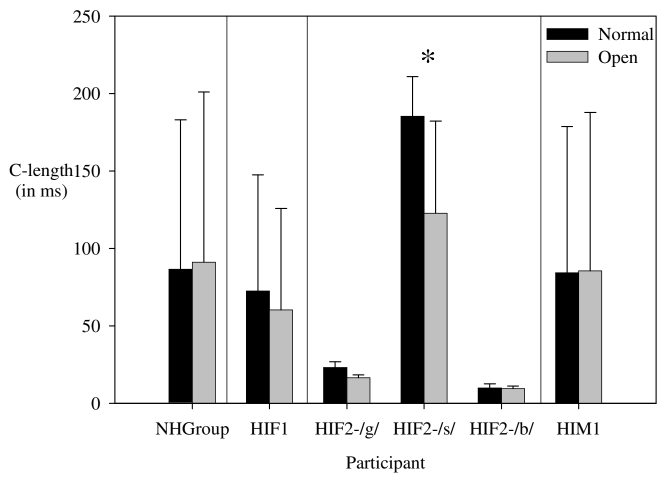


Figure 13. Jaw effect on consonant length (C-length). Means and standard deviations of C-length for each of the vowels /i, a, u/ in the normal and open jaw conditions for the normal-hearing group (NHGroup) and the three hearing-impaired participants (HIF1, HIF2, HIM1). Data showing a significant consonant and jaw interaction effect were presented in the three consonant (/g, s, b/) contexts separately. Significantly different pairs in each data set were marked with an asterisk ("*").

Figure 14.1: Vowel /i/

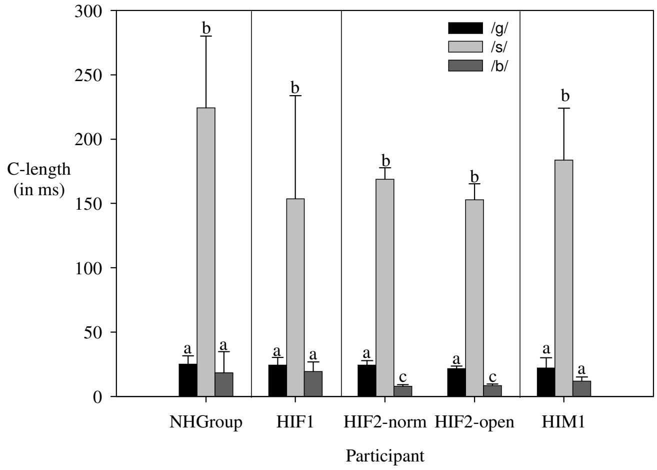


Figure 14.2: Vowel /a/

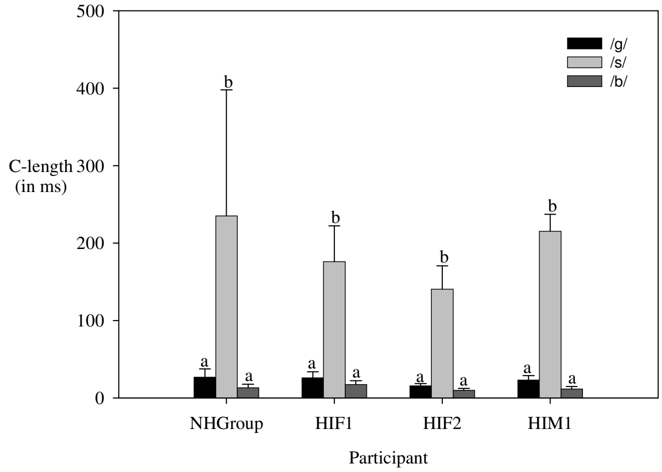


Figure 14.3: Vowel /u/

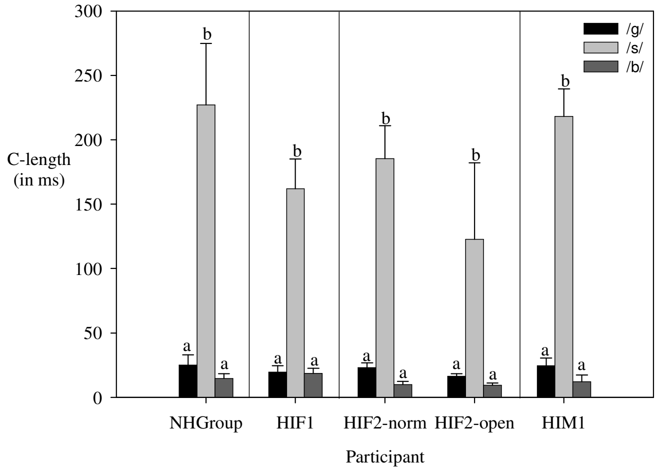


Figure 14. Consonant effect on consonant length (C-length). Means and standard deviations of C-length for each of the vowels /i, a, u/ in the three consonant (/g, s, b/) contexts for the normal-hearing group (NHGroup) and the three hearing-impaired participants (HIF1, HIF2, HIM1). Data showing a significant consonant and jaw interaction effect were presented in the normal ("norm") and open jaw conditions separately. Significantly different pairs in each data set were marked with different letters.

Figure 15.1: Vowel /i/

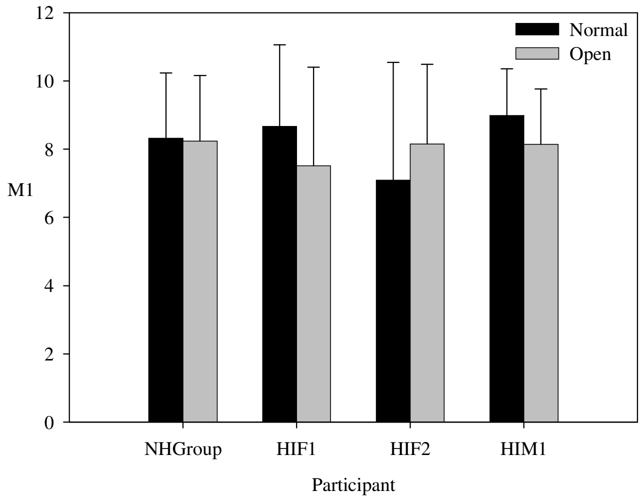


Figure 15.2: Vowel /a/

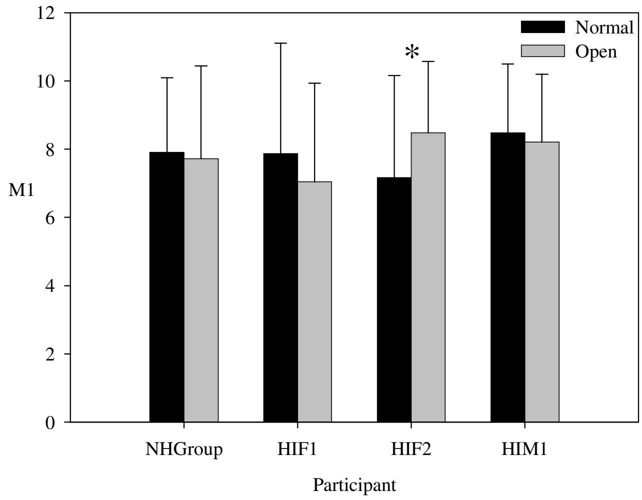


Figure 15.3: Vowel /u/

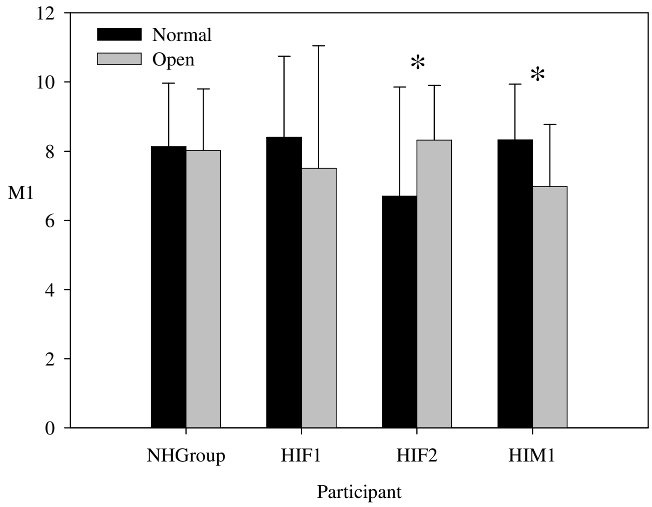


Figure 15. Jaw effect on Moment one (M1). Means and standard deviations of M1 (in kHz) for each of the vowels /i, a, u/ in the normal and open jaw conditions for the normal-hearing group (NHGroup) and the three hearing-impaired participants (HIF1, HIF2, HIM1). Significantly different pairs in each data set were marked with an asterisk (“*”).

Figure 16.1: Vowel /i/

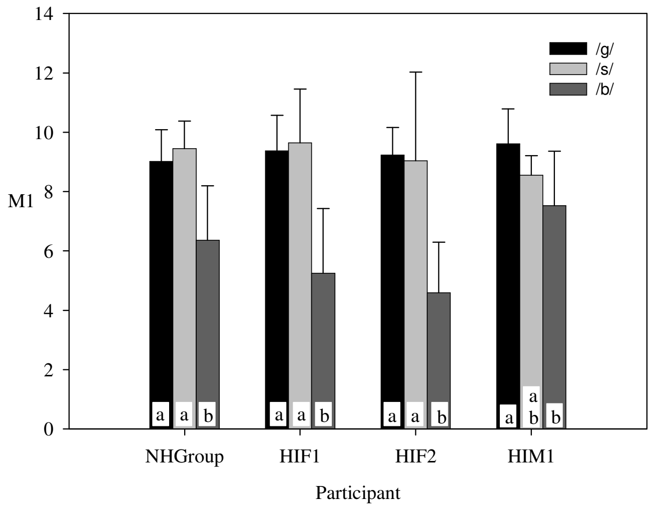


Figure 16.2: Vowel /a/

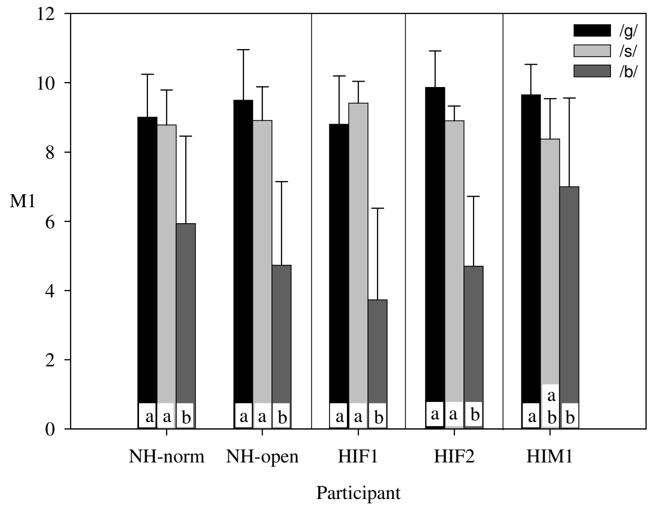


Figure 16.3: Vowel /u/

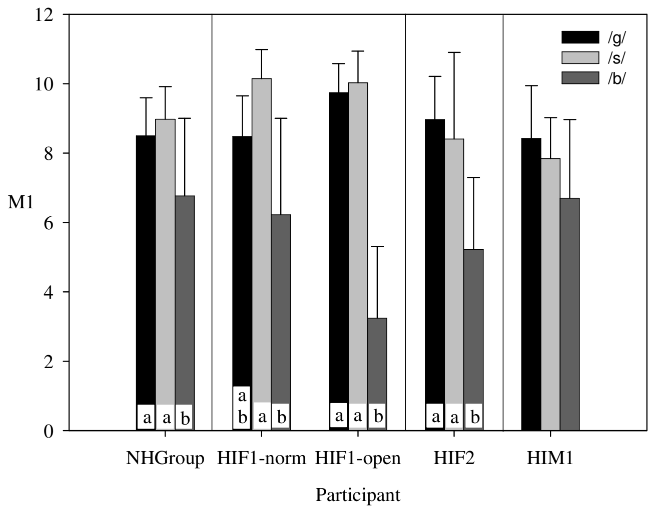


Figure 16. Consonant effect on Moment one (M1). Means and standard deviations of M1 (in kHz) for each of the vowels /i, a, u/ in the three consonant (/g, s, b/) contexts for the normal-hearing group (NHGroup) and the three hearing-impaired participants (HIF1, HIF2, HIM1). Significantly different pairs in each data set were marked with different letters.

Figure 17.1: Vowel /i/

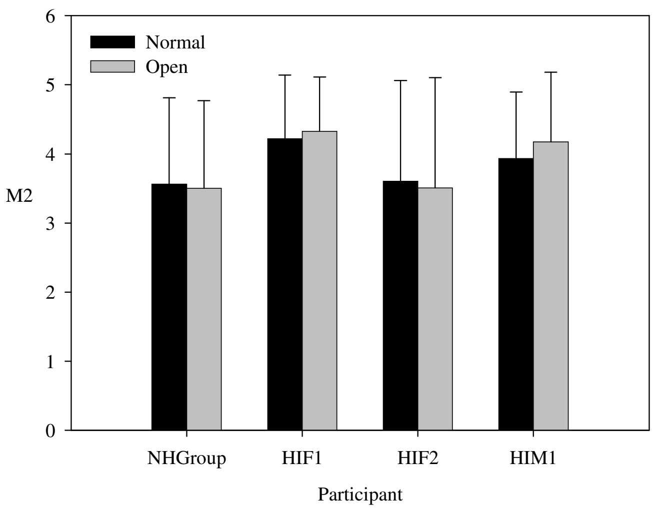


Figure 17.2: Vowel /a/

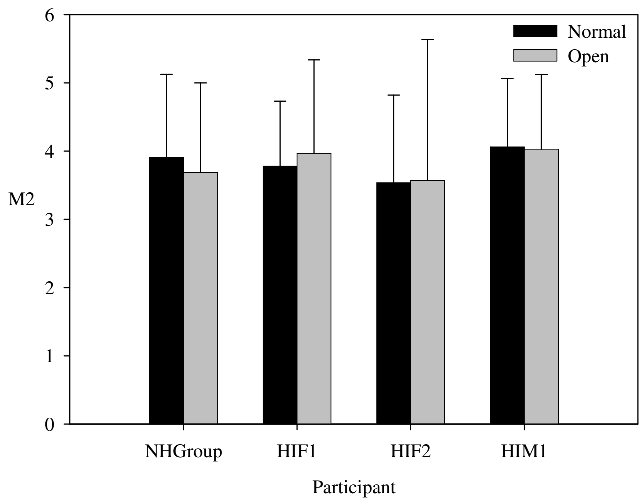


Figure 17.3: Vowel /u/

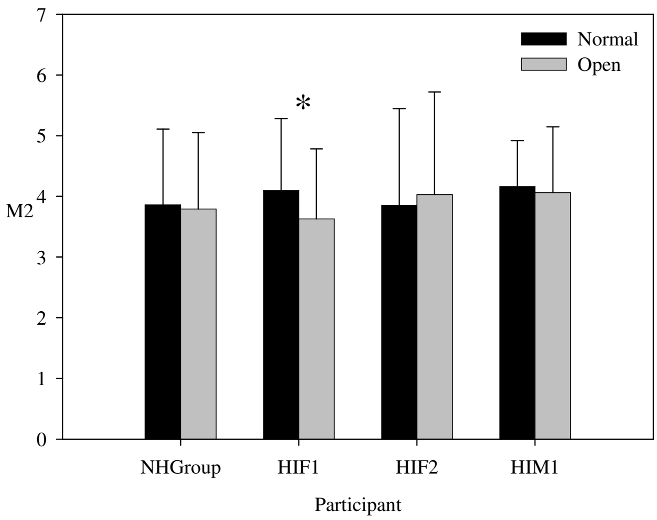


Figure 17. Jaw effect on Moment two (M2). Means and standard deviations of M2 (in kHz) for each of the vowels /i, a, u/ in the normal and open jaw conditions for the normal-hearing group (NHGroup) and the three hearing-impaired participants (HIF1, HIF2, HIM1). Significantly different pairs in each data set were marked with an asterisk ("*").

Figure 18.1: Vowel /i/

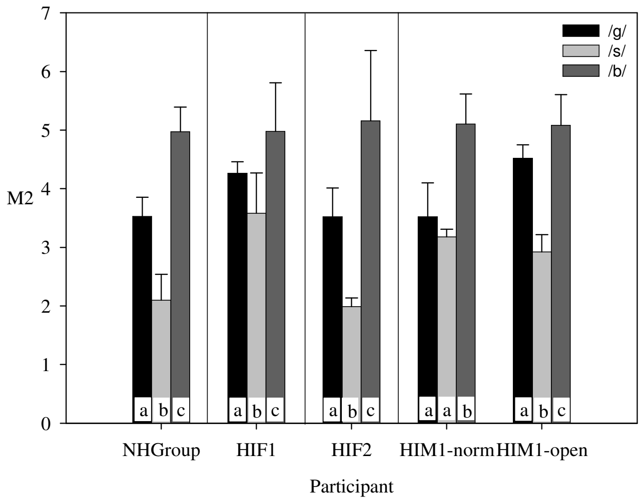


Figure 18.2: Vowel /a/

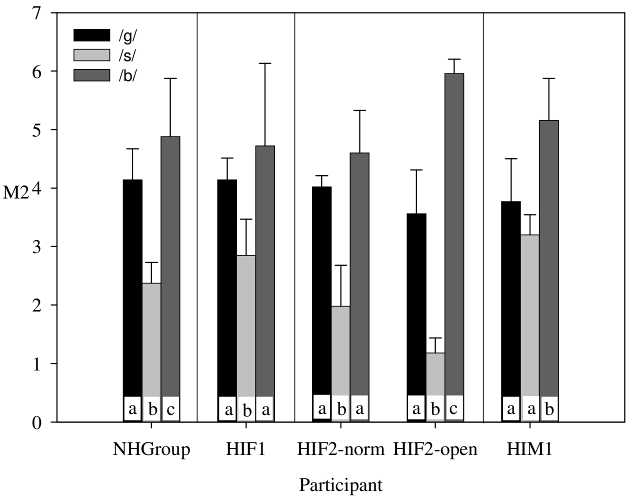


Figure 18.3: Vowel /u/

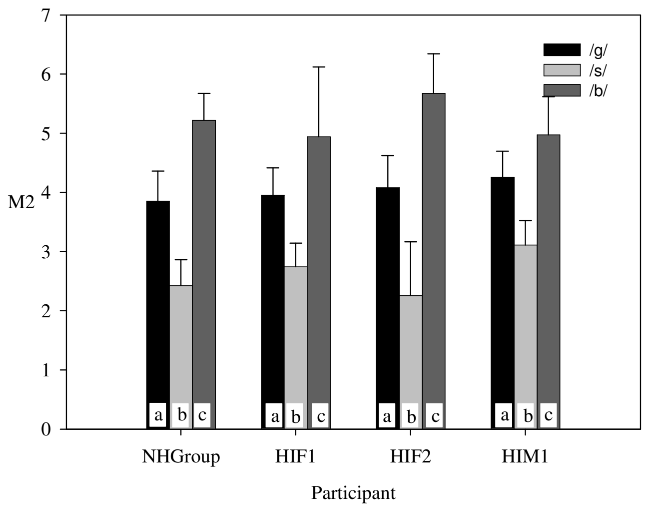


Figure 18. Consonant effect on Moment two (M2). Means and standard deviations of M2 (in kHz) for each of the vowels /i, a, u/ in the three consonant (/g, s, b/) contexts for the normal-hearing group (NHGroup) and the three hearing-impaired participants (HIF1, HIF2, HIM1). Data showing a significant consonant and jaw interaction effect were presented in the normal ("norm") and open jaw conditions separately. Significantly different pairs in each data set were marked with different letters.

Figure 19.1: Vowel /i/

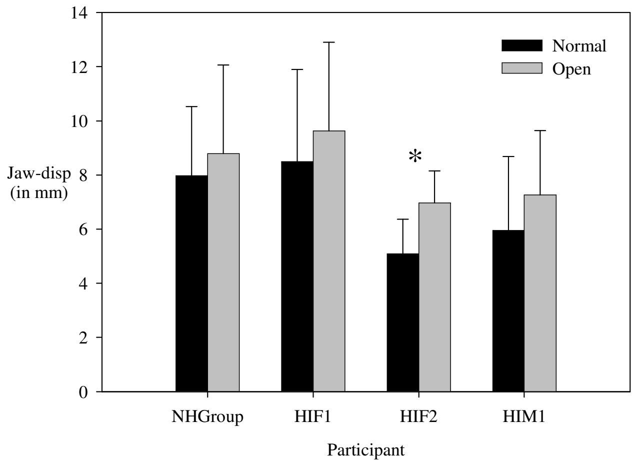


Figure 19.2: Vowel /a/

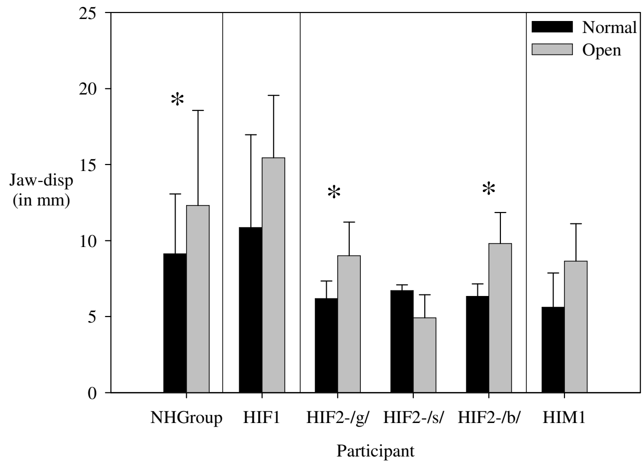


Figure 19.3: Vowel /u/

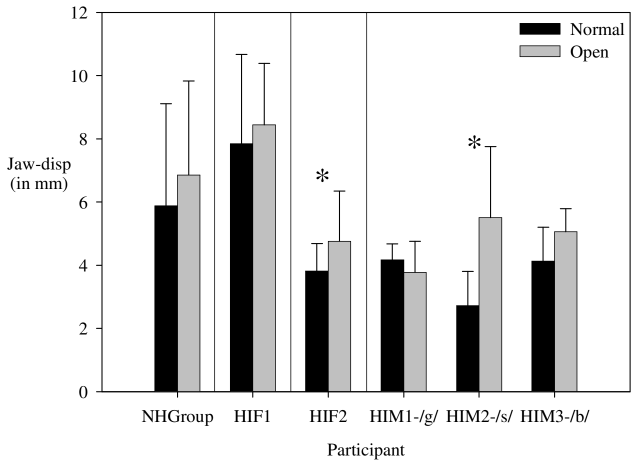


Figure 19. Jaw effect on jaw displacement (Jaw-disp). Means and standard deviations of Jaw-dsp for each of the vowels /i, a, u/ in the normal and open jaw conditions for the normal-hearing group (NHGroup) and the three hearing-impaired participants (HIF1, HIF2, HIM1). Data showing a significant consonant and jaw interaction effect were presented in the three consonant (/g, s, b/) contexts separately. Significantly different pairs in each data set were marked with an asterisk ("*").

Figure 20.1: Vowel /i/

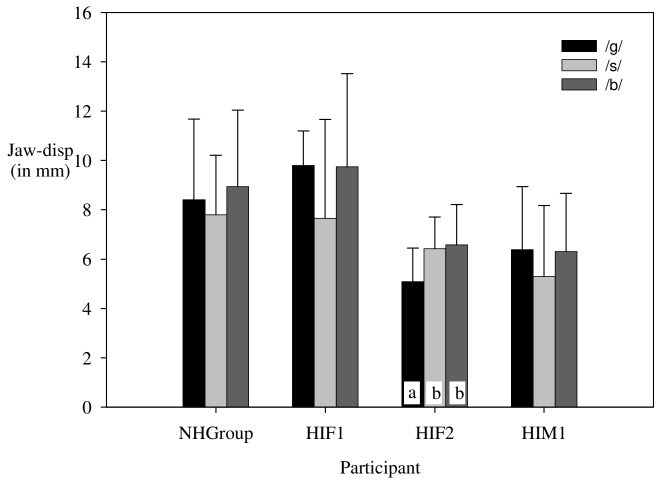


Figure 20.2: Vowel /a/

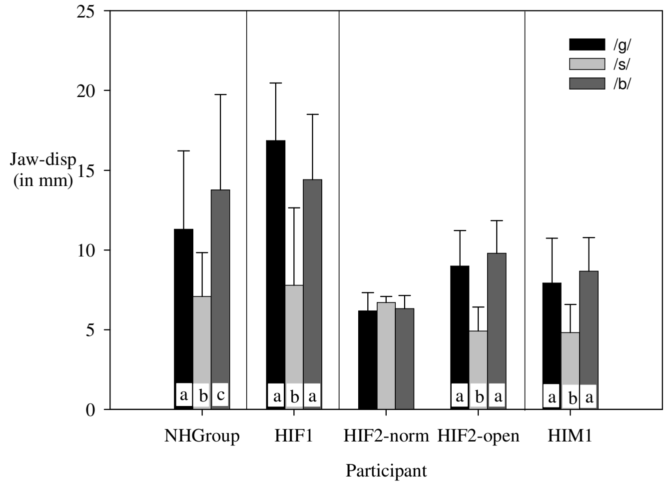


Figure 20.3: Vowel /u/

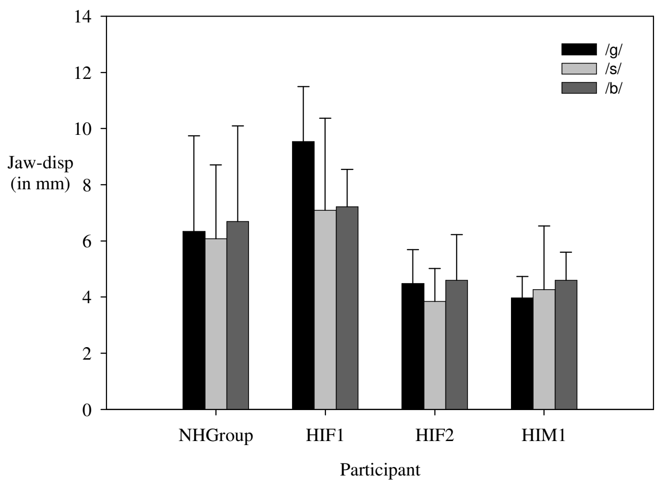


Figure 20. Consonant effect on jaw displacement (Jaw-dsp). Means and standard deviations of Jaw-dsp for eachthe vowels /i, a, u/ in the three consonant (/g, s, b/) contexts for the normal-hearing group (NHGroup) and the three hearing-impaired participants (HIF1, HIF2, HIM1). Data showing a significant consonant and jaw interaction effect were presented in the normal ("norm") and open jaw conditions separately. Significantly different pairs in each data set were marked with different letters.

Appendix 1
Normal-hearing participant information

Participant	Hearing level	Age	Gender	Goldman-Fristoe Score (no. sounds misarticulated)	Percentile Rank Norms	Misarticulated phoneme
1	Normal range	11	female	0	99	n/a
2	Normal range	12	female	0	99	n/a
3	Normal range	11	female	0	99	n/a
4	Normal range	9	female	0	99	n/a
5	Normal range	9	male	0	99	n/a
6	Normal range	12	male	1	68	/r/ /w/
7	Normal range	12	male	1	68	‘th’ /d/
8	Normal range	10	male	0	99	n/a
9	Normal range	11	male	0	99	n/a

Appendix 2

Hearing-impaired participant information

Participant	Hearing level	Age	Gender	Age of Onset	Age H/L Detected	Goldman-Fristoe Score	Percentile Rank Norms	Misarticulated phonemes
HIF1	Moderate/profound	11	Female	From birth	5	3	19	‘dj’ ’ch’; /d/ /t/ omission of initial /v/
HIM1	Severe/profound	12	Male	From birth: progressive	2	1	68	Medial /s/ ‘th’
HIF2	Mild to moderate	10	Female	From birth	4	0	99	n/a
HIF3*	Severe to profound	12	Female	Age 3	3	6	10	t/, /s/, ‘ch’, /z/, ‘dj’, ‘sl’, ‘st’, /k^w/ ’sh’; /g/ Ø; /n/ /l/; /v/ /f/; /l/ /m/; ‘th’ /d/; consonant cluster reduction,
HIM2*	Moderate/profound	9	Male	From birth	5	10	9	‘dr’ /r/, ‘fl’ /f/, interdental /s/ tΣ≅z; ‘ch’ /Σ/; initial consonant deletion; medial st ?; /t/ /l/; /s/ Ø; ‘dj’ /Σ/
HIM3*	Severe to profound	7	Male	From birth	3	26	1-	Interdental /z/ /s/; Interdental /z/ ’th’; ‘th’ /b/; ‘fl’ ’bl’; /sk^w/ /k^w/; /st/ /d/

* Recorded by a prievious student.

Appendix 3

Goldman-Fristoe Test of Articulation

1. house
2. telephone
3. Cup
4. Gun
5. knife
6. window
7. wagon
8. wheel
9. chicken
10. zipper
11. scissors
12. duck
13. yellow
14. vacuum
15. matches
16. lamp
17. shovel
18. car
19. rabbit
20. fishing
21. church
22. feather
23. pencils
24. this
25. carrot
26. orange
27. bathtub
28. bath
29. thumb
30. finger
31. ring
32. Jumping
33. Pajamas
34. Plane
35. blue
36. Brush
37. Drum
38. Flag
39. Santa Claus
40. Christmas tree
41. Squirrel
42. Sleeping
43. stove

Appendix 4

Second word list

Sue	Bar	Geese
See	Bee	Goose
Sob	Boot	Gaga
See	Bee	Geese
Sob	Bar	Gaga
Sue	Boot	Goose
See	Bee	Gaga
Sue	Boot	Geese
Sob	Bar	Goose
Sob	Boot	Gaga
Sue	Bee	Goose
See	Bar	Geese
Sob	Boot	Goose
See	Bar	Gaga
Sue	Bee	Geese

Appendix 5

Words taken from Goldman-Fristoe Test of Articulation for nasality measures.

cup

gun

window

wagon

wheel

zipper

sissors

duck

shovel

car

fishing

this

thumb

finger

ring

jumping

brush

drum

sleeping

Appendix 6

Two-way (Consonant by jaw) ANOVA results for individuals in the normal-hearing group: Formant one.

Subject	N	Jaw Effect	Consonant Effect	Consonant x Jaw Interaction
/i/				
F1	30	$F(1, 24) = 0.020, p = 0.888$	$F(2, 24) = 2.135, p = 0.140$	$F(2, 24) = 0.105, p = 0.900$
F2	29[†]	$F(1, 23) = 1.339, p = 0.259$	$F(2, 23) = 1.564, p = 0.231$	$F(2, 23) = 1.222, p = 0.313$
F3	30	$F(1, 24) = 1.004, p = 0.326$	$F(2, 24) = 2.904, p = 0.074$	$F(2, 24) = 0.229, p = 0.797$
F4	30	$F(1, 24) = 1.253, p = 0.274$	$F(2, 24) = 3.907, p = 0.034$	$F(2, 24) = 2.266, p = 0.125$
M1	30	$F(1, 24) = 3.435, p = 0.076$	$F(2, 24) = 0.917, p = 0.413$	$F(2, 24) = 1.836, p = 0.181$
M2	30	$F(1, 24) = 0.039, p = 0.846$	$F(2, 24) = 8.673, p = 0.001$*	$F(2, 24) = 0.575, p = 0.570$
M3	30	$F(1, 24) = 1.864, p = 0.185$	$F(2, 24) = 1.427, p = 0.260$	$F(2, 24) = 2.316, p = 0.120$
M4	30	$F(1, 24) = 1.738, p = 0.200$	$F(2, 24) = 6.636, p = 0.005$*	$F(2, 24) = 0.527, p = 0.597$
M5	30	$F(1, 24) = 2.168, p = 0.154$	$F(2, 24) = 6.188, p = 0.007$*	$F(2, 24) = 2.285, p = 0.123$
/a/				
F1	30	$F(1, 24) = 1.841, p = 0.187$	$F(2, 23) = 91.235, p < 0.001$**	$F(2, 24) = 1.833, p = 0.182$
F2	29[†]	$F(1, 23) = 0.980, p = 0.332$	$F(2, 23) = 5.269, p = 0.013$*	$F(2, 23) = 0.405, p = 0.672$
F3	30	$F(1, 24) = 3.460, p = 0.075$	$F(2, 24) = 12.212, p < 0.001$**	$F(2, 24) = 0.285, p = 0.755$
F4	30	$F(1, 24) = 4.110, p = 0.054$	$F(2, 24) = 203.87, p < 0.001$**	$F(2, 24) = 2.528, p = 0.101$
M1	30	$F(1, 24) = 1.781, p = 0.195$	$F(2, 24) = 15.663, p < 0.001$**	$F(2, 24) = 0.102, p = 0.903$
M2	30	$F(1, 24) = 13.640, p = 0.001$*	$F(2, 24) = 199.92, p < 0.001$**	$F(2, 24) = 2.474, p = 0.105$
M3	30	$F(1, 24) = 1.216, p = 0.281$	$F(2, 24) = 72.23, p < 0.001$**	$F(2, 24) = 0.606, p = 0.554$
M4	30	$F(1, 24) = 38.868, p < 0.001$**	$F(2, 24) = 95.826, p < 0.001$**	$F(2, 24) = 4.218, p = 0.027$*
M5	30	$F(1, 24) = 0.037, p = 0.849$	$F(2, 24) = 124.65, p < 0.001$**	$F(2, 24) = 1.390, p = 0.268$
/u/				
F1	30	$F(1, 24) = 0.763, p = 0.391$	$F(2, 24) = 18.220, p < 0.001$**	$F(2, 24) = 0.591, p = 0.561$
F2	30	$F(1, 24) = 0.183, p = 0.673$	$F(2, 24) = 1.415, p = 0.263$	$F(2, 24) = 0.802, p = 0.460$
F3	30	$F(1, 24) = 9.492, p = 0.005$*	$F(2, 24) = 8.010, p = 0.002$*	$F(2, 24) = 0.846, p = 0.442$
F4	30	$F(1, 24) = 1.965, p = 0.174$	$F(2, 24) = 0.180, p = 0.837$	$F(2, 24) = 1.832, p = 0.182$
M1	29[†]	$F(1, 24) = 0.952, p = 0.339$	$F(2, 24) = 0.873, p = 0.431$	$F(2, 24) = 1.158, p = 0.331$
M2	30	$F(1, 24) = 0.495, p = 0.489$	$F(2, 24) = 2.463, p = 0.106$	$F(2, 24) = 1.253, p = 0.304$
M3	30	$F(1, 24) = 0.381, p = 0.543$	$F(2, 24) = 0.170, p = 0.844$	$F(2, 24) = 2.924, p = 0.073$
M4	30	$F(1, 24) = 17.943, p < 0.001$**	$F(2, 24) = 0.522, p = 0.600$	$F(2, 24) = 0.987, p = 0.387$
M5	29[†]	$F(1, 23) = 7.965, p = 0.010$*	$F(2, 23) = 12.108, p < 0.001$**	$F(2, 23) = 2.501, p = 0.104$

*Significant at 0.05 level

**Significant at 0.005 level

[†]Missing data

Appendix 7

Two-way (Consonant by jaw) ANOVA results for individuals in the normal-hearing group: Formant two.

Subject	N	Jaw Effect	Consonant Effect	Consonant x Jaw Interaction
/i/				
F1	30	F(1, 24) = 0.038, p = 0.847	F(2, 24) = 0.624, p = 0.544	F(2, 24) = 0.578, p = 0.568
F2	29[†]	F(1, 23) = 3.765, p = 0.065	F(1, 23) = 2.539, p = 0.101	F(2, 23) = 2.881, p = 0.076
F3	30	F(1, 24) = 17.703, p < 0.001**	F(2, 24) = 6.245, p = 0.007*	F(2, 24) = 0.125, p = 0.883
F4	30	F(1, 24) = 0.003, p = 0.958	F(2, 24) = 4.636, p = 0.019*	F(2, 24) = 0.149, p = 0.862
M1	30	F(1, 24) = 4.108, p = 0.054	F(2, 24) = 0.853, p = 0.439	F(2, 24) = 3.045, p = 0.066
M2	30	F(1, 24) = 5.624, p = 0.026*	F(2, 24) = 1.142, p = 0.336	F(2, 24)= 0.724, p = 0.495
M3	30	F(1, 24) = 16.166, p < 0.001**	F(2, 24) = 3.545, p = 0.045*	F(2, 24) = 1.547, p = 0.233
M4	30	F(1, 24) = 0.015, p = 0.903	F(2, 24) = 0.852, p = 0.439	F(2, 24) = 0.531, p = 0.595
M5	30	F(1, 24) = 3.633, p = 0.069	F(2, 24) = 2.264, p = 0.126	F(2, 24) = 5.706, p = 0.009*
/a/				
F1	29[†]	F(1, 24) = 14.57, p < 0.001**	F(2, 24) = 14.522, p < 0.001**	F(2, 24) = 12.657, p < 0.001**
F2	29[†]	F(1, 23) = 7.411, p = 0.012*	F(2, 23) = 109.261, p < 0.001**	F(2, 23) = 1.140, p = 0.337
F3	30	F(1, 24) = 0.510, p = 0.482	F(2, 24) = 60.631, p < 0.001**	F(2, 24) = 1.311, p = 0.288
F4	30	F(1, 24) = 145.685, p < 0.001**	F(2, 24) = 365.034, p < 0.001**	F(2, 24) = 27.645, p < 0.001**
M1	30	F(1, 24) = 1.348, p = 0.257	F(2, 24) = 21.997, p < 0.001**	F(2, 24) = 0.034, p = 0.967
M2	30	F(1, 24) = 7.810, p = 0.010*	F(2, 24) = 362.301, p < 0.001**	F(2, 24) = 0.700, p = 0.507
M3	30	F(1, 24) = 3.425, p = 0.077	F(2, 24) = 218.903, p < 0.001**	F(2, 24) = 2.491, p = 0.104
M4	30	F(1, 24) = 0.301, p = 0.588	F(2, 24) = 145.324, p < 0.001**	F(2, 24) = 1.834, p = 0.181
M5	30	F(1, 24) = 0.971, p = 0.334	F(2, 24) = 228.161, p < 0.001**	F(2, 24) = 0.034, p = 0.967
/u/				
F1	30	F(1, 24) = 0.611, p= 0.442	F(2, 24) = 1.251, p = 0.304	F(2, 24) = 2.000, p = 0.157
F2	30	F(1, 24) = 5.085, p= 0.034*	F(2, 24) = 0.168, p = 0.846	F(2, 24) = 0.538, p = 0.591
F3	30	F(1, 24) = 0.862, p= 0.362	F(2, 24) = 2.296, p = 0.122	F(2, 24) = 1.132, p = 0.339
F4	30	F(1, 24) = 6.603, p = 0.017*	F(2, 24) = 15.954, p < 0.001**	F(2, 24) = 0.921, p = 0.412
M1	30	F(1, 24) = 1.586, p = 0.220	F(2, 24) = 1.297, p = 0.292	F(2, 24) = 0.540, p = 0.589
M2	30	F(1, 24) = 4.907, p = 0.036*	F(2, 24) = 5.527, p = 0.011*	F(2, 24) = 4.230, p = 0.027*
M3	30	F(1, 24) = 0.251, p = 0.621	F(2, 24) = 0.493, p = 0.617	F(2, 24) = 0.554, p = 0.582
M4	30	F(1, 24) = 0.119, p = 0.733	F(2, 24) = 6.696, p = 0.005*	F(2, 24) = 0.405, p = 0.672
M5	29[†]	F(1, 23) = 1.854, p = 0.187	F(2, 23) = 4.969, p = 0.016*	F(2, 23) = 2.034, p = 0.154

*Significant at 0.05 level
**Significant at 0.005 level
[†]Missing data

Appendix 8

Two-way (Consonant by jaw) ANOVA results for individuals in the normal-hearing group:

Fundamental frequency.

Subject	N	Jaw Effect	Consonant Effect	Consonant x Jaw Interaction
/i/				
F1	30	F(1, 24) = 2.595, p = 0.120	F(2, 24) = 2.443, p = 0.108	F(2, 24) = 1.667, p = 0.210
F2	29†	F(1, 23) = 1.923, p = 0.179	F(2, 23) = 4.966, p = 0.016*	F(2, 23) = 0.337, p = 0.717
F3	30	F(1, 24) = 3.008, p = 0.096	F(2, 24) = 1.152, p = 0.333	F(2, 24) = 0.645, p = 0.534
F4	30	F(1, 24) = 1.572, p = 0.222	F(2, 24) = 5.199, p = 0.013*	F(2, 24) = 1.048, p = 0.366
M1	30	F(1, 24) = 2.685, p = 0.114	F(2, 24) = 16.320, p < 0.001**	F(2, 24) = 2.084, p = 0.146
M2	30	F(1, 24) = 1.208, p = 0.283	F(2, 24) = 3.222, p = 0.058	F(2, 24) = 1.935, p = 0.166
M3	30	F(1, 24) = 2.597, p = 0.120	F(2, 24) = 8.066, p = 0.002*	F(2, 24) = 0.387, p = 0.683
M4	30	F(1, 24) = 4.440, p = 0.046*	F(2, 24) = 2.924, p = 0.073	F(2, 24) = 2.086, p = 0.146
M5	30	F(1, 24) = 23..99, p < 0.001**	F(2, 24) = 4.895, p = 0.016*	F(2, 24) = 0.434, p = 0.653
/a/				
F1	30	F(1, 24) = 3.749, p = 0.065	F(2, 24) = 13.286, p < 0.001**	F(2, 24) = 0.378, p = 0.689
F2	29†	F(1, 23) = 0.468, p = 0.501	F(2, 23) = 0.147, p = 0.864	F(2, 23) = 0.831, p = 0.448
F3	30	F(1, 24) = 30.579, p < 0.001**	F(2, 24) = 2.436, p = 0.109	F(2, 24) = 0.159, p = 0.854
F4	30	F(1, 24) = 0.089, p = 0.768	F(1, 24) = 33.090, p < 0.001**	F(2, 24) = 0.124, p = 0.884
M1	30	F(1, 24) = 4.906, p = 0.037*	F(2, 24) = 12.590, p < 0.001**	F(2, 24) = 0.947, p = 0.402
M2	30	F(1, 24) = 3.628, p = 0.069	F(2, 24) = 29.040, p < 0.001**	F(2, 24) = 0.012, p = 0.988
M3	30	F(1, 24) = 0.835, p = 0.370	F(2, 24) = 11.675, p < 0.001**	F(2, 24) = 0.104, p = 0.901
M4	30	F(1, 24) = 0.390, p = 0.538	F(2, 24) = 1.673, p = 0.209	F(2, 24) = 1.338, p = 0.281
M5	30	F(1, 24) = 41.484, p < 0.001**	F(2, 24) = 4.048, p = 0.031*	F(2, 24) = 0.652, p = 0.530
/u/				
F1	29†	F(1, 24) = 7.886, p = 0.010*	F(2, 24) = 9.505, p < 0.001**	F(2, 24) = 1.305, p = 0.290
F2	30	F(1, 24) = 3.410, p = 0.077	F(2, 24) = 2.441, p = 0.108	F(2, 24) = 1.527, p = 0.237
F3	30	F(1, 24) = 41.640, p < 0.001**	F(2, 24) = 11.638, p < 0.001**	F(2, 24) = 22.464, p < 0.001**
F4	30	F(1, 24) = 2.982, p = 0.097	F(2, 24) = 2.610, p = 0.094	F(2, 24) = 1.756, p = 0.194
M1	30	F(1, 24) = 3.561, p = 0.071	F(2, 24) = 1.991, p = 0.158	F(2, 24) = 0.658, p = 0.527
M2	30	F(1, 24) = 5.879, p = 0.023*	F(2, 24) = 1.816, p = 0.184	F(2, 24) = 1.360, p = 0.276
M3	30	F(1, 24) = 0.833, p = 0.370	F(2, 24) = 0.861, p = 0.435	F(2, 24) = 1.596, p = 0.223
M4	30	F(1, 24) = 4.581, p = 0.043*	F(2, 24) = 0.067, p = 0.935	F(2, 24) = 0.598, p = 0.558
M5	29†	F(1, 23) = 24.161, p < 0.001**	F(2, 23) = 16.487, p < 0.001**	F(2, 23) = 2.112, p = 0.144

*Significant at 0.05 level
**Significant at 0.005 level
†Missing data

Appendix 9

Two-way (Consonant by jaw) ANOVA results for individuals in the normal-hearing group: Percent jitter.

Subject	N	Jaw Effect	Consonant Effect	Consonant x Jaw Interaction
/i/				
F1	30	F(1, 24) = 0.457, p = 0.506	F(2, 24) = 1.239, p = 0.307	F(2, 24) = 1.033, p = 0.371
F2	29†	F(1, 23) = 0.093, p = 0.764	F(2, 23) = 1.136, p = 0.338	F(2, 23) = 3.819, p = 0.037*
F3	30	F(1, 24) = 0.138, p = 0.713	F(2, 24) = 0.869, p = 0.432	F(2, 24) = 0.182, p = 0.835
F4	30	F(1, 24) = 0.954, p = 0.338	F(2, 24) = 0.144, p = 0.867	F(2, 24) = 0.709, p = 0.502
M1	30	F(1, 24) = 0.011, p = 0.918	F(2, 24) = 1.427, p = 0.260	F(2, 24) = 1.416, p = 0.262
M2	30	F(1, 24) = 2.194, p = 0.152	F(2, 24) = 2.028, p = 0.154	F(2, 24) = 0.147, p = 0.864
M3	30	F(1, 24) = 0.137, p = 0.714	F(2, 24) = 0.113, p = 0.894	F(2, 24) = 0.694, p = 0.509
M4	30	F(1, 24) = 4.498, p = 0.044*	F(2, 24) = 0.681, p = 0.516	F(2, 24) = 1.568, p = 0.229
M5	30	F(1, 24) = 5.104, p = 0.033*	F(2, 24) = 0.094, p = 0.911	F(2, 24) = 0.121, p = 0.887
/a/				
F1	30	F(1, 24) = 3.017, p= 0.095	F(2, 24) = 4.691, p = 0.019*	F(2, 24) = 1.399, p = 0.266
F2	29†	F(1, 23) = 0.040, p = 0.842	F(2, 23) = 0.322, p = 0.728	F(2, 23) = 3.981, p = 0.033*
F3	30	F(1, 24) = 4.731, p = 0.040*	F(2, 24) = 0.885, p = 0.426	F(2, 24) = 0.438, p = 0.650
F4	30	F(1, 24) = 3.290, p = 0.082	F(2, 24) = 4.826, p = 0.017*	F(2, 24) = 2.030, p = 0.153
M1	30	F(1, 24) = 0.118, p = 0.735	F(2, 24) = 1.261, p = 0.301	F(2, 24) = 5.019, p = 0.015*
M2	30	F(1, 24) = 3.490, p = 0.074	F(2, 24) = 4.118, p = 0.029*	F(2, 24) = 0.592, p = 0.561
M3	30	F(1, 24) = 1.924, p = 0.178	F(2, 24) = 0.699, p = 0.507	F(2, 24) = 1.869, p = 0.176
M4	30	F(1, 24) = 8.078, p = 0.009*	F(2, 24) = 1.470, p = 0.250	F(2, 24) = 0.870, p = 0.432
M5	30	F(1, 24) = 4.597, p = 0.042*	F(2, 24) = 0.813, p = 0.455	F(2, 24) = 0.864, p = 0.434
/u/				
F1	30	F(1, 24) = 0.071, p= 0.792	F(2, 24) = 8.963, p = 0.001*	F(2, 24) = 0.891, p = 0.423
F2	30	F(1, 24) = 1.466, p= 0.238	F(2, 24) = 0.581, p = 0.567	F(2, 24) = 1.552, p = 0.232
F3	30	F(1, 24) = 2.037, p= 0.166	F(2, 24) = 0.861, p = 0.435	F(2, 24) = 2.093, p = 0.145
F4	30	F(1, 24) = 0.018, p= 0.894	F(2, 24) = 7.758, p = 0.003*	F(2, 24) = 0.866, p = 0.433
M1	30	F(1, 24) = 2.522, p = 0.125	F(2, 24) = 4.566, p = 0.021`*	F(2, 24) = 1.817, p = 0.184
M2	30	F(1, 24) = 13.201, p = 0.001*	F(2, 24) = 2.454, p = 0.107	F(2, 24) = 3.695, p = 0.040*
M3	30	F(1, 24) = 1.809, p = 0.191	F(2, 24) = 4.225, p = 0.027	F(1, 24) = 0.100, p = 0.905
M4	30	F(1, 24) = 8.884, p = 0.006*	F(2, 24) = 4.003, p = 0.032*	F(2, 24) = 1.222, p = 0.312
M5	29†	F(1, 23) = 11.634, p = 0.002*	F(2, 23) = 0.330, p = 0.722	F(2, 23) = 0.311, p = 0.736

*Significant at 0.05 level
**Significant at 0.005 level
†Missing data

Appendix 10

Two-way (Consonant by jaw) ANOVA results for individuals in the normal-hearing group: Percent shimmer.

Subject	N	Jaw Effect	Consonant Effect	Consonant x Jaw Interaction
/i/				
F1	30	F(1, 24) = 0.916, p = 0.348	F(2, 24) = 1.371, p = 0.273	F(2, 24) = 0.542, p = 0.588
F2	29[†]	F(1, 23) = 0.251, p = 0.621	F(2, 23) = 4.642, p = 0.020*	F(2, 23) = 3.710, p = 0.040*
F3	30	F(1, 24) = 0.030, p = 0.865	F(2, 24) = 1.173, p = 0.326	F(2, 24) = 0.095, p = 0.909
F4	30	F(1, 24) = 2.341, p = 0.139	F(2, 24) = 2.227, p = 0.130	F(2, 24) = 1.376, p = 0.272
M1	30	F(1, 24) = 0.644, p = 0.430	F(2, 24) = 0.911 p = 0.415	F(2, 24) = 0.560, p = 0.579
M2	30	F(1, 24) = 0.002, p = 0.966	F(2, 24) = 0.519, p = 0.602	F(2, 24) = 0.266, p = 0.768
M3	30	F(1, 24) = 0.069, p = 0.796	F(2, 24) = 0.148, p = 0.863	F(2, 24) = 0.237, p = 0.791
M4	30	F(1, 24) = 3.464, p = 0.075	F(2, 24) = 2.711, p = 0.087	F(2, 24) = 2.211, p = 0.131
M5	30	F(1, 24) = 8.946, p = 0.006*	F(2, 24) = 0.047, p = 0.954	F(2, 24) = 0.288, p = 0.752
/a/				
F1	30	F(1, 24) = 0.106, p= 0.748	F(2, 24) = 9.693, p < 0.001**	F(2, 24) = 0.772, p = 0.473
F2	29[†]	F(1, 23) = 1.760, p= 0.198	F(2, 23) = 2.330, p = 0.120	F(2, 23) = 3.904, p = 0.035*
F3	30	F(1, 24) = 4.565, p= 0.043*	F(2, 24) = 0.987, p = 0.387	F(2, 24) = 0.042, p = 0.959
F4	30	F(1, 24) = 2.465, p= 0.129	F(2, 24) = 1.324, p = 0.285	F(2, 24) = 0.904, p = 0.418
M1	30	F(1, 24) = 0.747, p = 0.396	F(2, 24) = 0.348, p = 0.709	F(2, 24) = 4.427, p = 0.023*
M2	30	F(1, 24) = 4.533, p = 0.044*	F(2, 24) = 1.685, p = 0.207	F(2, 24) = 0.939, p = 0.405
M3	30	F(1, 24) = 0.003, p = 0.960	F(2, 24) = 2.777, p = 0.082	F(2, 24) = 4.295, p = 0.025*
M4	30	F(1, 24) = 4.643, p = 0.041*	F(2, 24) = 1.440, p = 0.257	F(2, 24) = 1.329, p = 0.284
M5	30	F(1, 24) = 6.602, p = 0.017*	F(2, 24) = 0.960, p = 0.397	F(2, 24) = 1.213, p = 0.315
/u/				
F1	30	F(1, 24) = 1.946, p = 0.176	F(2, 24) = 13.060, p = 0.001*	F(2, 24) = 1.156, p = 0.332
F2	30	F(1, 24) = 1.423, p = 0.245	F(2, 24) = 1.487, p = 0.246	F(2, 24) = 1.003, p = 0.382
F3	30	F(1, 24) = 1.817, p = 0.190	F(2, 24) = 1.017, p = 0.377	F(2, 24) = 0.510, p = 0.607
F4	30	F(1, 24) = 2.195, p = 0.151	F(2, 24) = 8.338, p = 0.002**	F(2, 24) = 1.724, p = 0.200
M1	30	F(1, 24) = 0.952, p = 0.339	F(2, 24) = 11.033, p < 0.001**	F(2, 24) = 0.933, p = 0.407
M2	30	F(1, 24) = 6.527, p = 0.017*	F(2, 24) = 41.494, p < 0.001**	F(2, 24) = 3.905, p = 0.034*
M3	30	F(1, 24) = 0.213, p = 0.648	F(2, 24) = 16.780, p < 0.001**	F(2, 24) = 0.586, p = 0.564
M4	30	F(1, 24) = 15.658, p < 0.001**	F(2, 24) = 16.142, p < 0.001**	F(2, 24) = 2.081, p = 0.147
M5	29[†]	F(1, 23) = 8.986, p = 0.006*	F(2, 23) = 45.095, p < 0.001**	F(2, 23) = 2.802, p = 0.081

*Significant at 0.05 level
**Significant at 0.005 level
[†]Missing data

Appendix 11

Two-way (Consonant by jaw) ANOVA Results for individuals in the normal-hearing group: Signal-to-noise ratio.

Subject	N	Jaw Effect	Consonant Effect	Consonant x Jaw Interaction
/i/				
F1	30	F(1, 24) = 1.630, p = 0.214	F(2, 24) = 3.887, p = 0.034*	F(2, 24) = 0.225, p = 0.800
F2	29†	F(1, 23) = 1.760, p = 0.198	F(2, 23) = 0.236, p = 0.792	F(2, 23) = 2.558, p = 0.099
F3	30	F(1, 24) = 1.893, p = 0.182	F(2, 24) = 0.340, p = 0.715	F(2, 24) = 0.581, p = 0.567
F4	30	F(1, 24) = 18.205, p < 0.001**	F(2, 24) = 0.726, p = 0.494	F(2, 24) = 0.974, p = 0.392
M1	30	F(1, 24) = 0.274, p = 0.606	F(2, 24) = 1.123, p = 0.342	F(2, 24) = 1.065, p = 0.361
M2	30	F(1, 24) = 0.142, p = 0.710	F(2, 24) = 1.761, p = 0.193	F(2, 24) = 3.614, p = 0.042*
M3	30	F(1, 24) = 0.254, p = 0.619	F(2, 24) = 0.676, p = 0.518	F(2, 24) = 0.579, p = 0.568
M4	30	F(1, 24) = 2.360, p = 0.138	F(2, 24) = 1.557, p = 0.231	F(2, 24) = 0.967, p = 0.395
M5	30	F(1, 24) = 1.410, p = 0.247	F(2, 24) = 2.666, p = 0.090	F(2, 24) = 1.348, p = 0.279
/a/				
F1	30	F(1, 24) = 0.297, p = 0.591	F(2, 24) = 2.465, p = 0.106	F(2, 24) = 1.219, p = 0.313
F2	29†	F(1, 23) = 3.138, p = 0.090	F(2, 23) = 1.292, p = 0.294	F(2, 23) = 5.381, p = 0.012*
F3	30	F(1, 24) = 1.491, p = 0.234	F(2, 24) = 2.110, p = 0.143	F(2, 24) = 1.368, p = 0.274
F4	30	F(1, 24) = 12.60, p = 0.002*	F(2, 24) = 0.482, p = 0.624	F(2, 24) = 0.260, p = 0.773
M1	30	F(1, 24) = 0.023, p = 0.880	F(2, 24) = 3.286, p = 0.055	F(2, 24) = 2.780, p = 0.082
M2	30	F(1, 24) = 3.220, p = 0.085	F(2, 24) = 3.177, p = 0.060	F(2, 24) = 1.546, p = 0.234
M3	30	F(1, 24) = 6.752, p = 0.016*	F(2, 24) = 18.915, p < 0.001**	F(2, 24) = 3.150, p = 0.061
M4	30	F(1, 24) = 5.232, p = 0.031*	F(2, 24) = 3.071, p = 0.065	F(2, 24) = 0.477, p = 0.627
M5	30	F(1, 24) = 4.528, p = 0.044*	F(2, 24) = 5.051, p = 0.015*	F(2, 24) = 1.379, p = 0.271
/u/				
F1	30	F(1, 24) = 1.544, p = 0.226	F(2, 24) = 5.081, p = 0.014*	F(2, 24) = 0.386, p = 0.684
F2	30	F(1, 24) = 4.836, p = 0.038*	F(2, 24) = 0.631, p = 0.541	F(2, 24) = 2.277, p = 0.124
F3	30	F(1, 24) = 0.067, p = 0.798	F(2, 24) = 6.136, p = 0.007*	F(2, 24) = 1.344, p = 0.280
F4	30	F(1, 24) = 1.948, p = 0.176	F(2, 24) = 3.626, p = 0.042*	F(2, 24) = 0.070, p = 0.933
M1	30	F(1, 24) = 2.824, p = 0.106	F(2, 24) = 3.386, p = 0.051	F(2, 24) = 5.902, p = 0.008*
M2	30	F(1, 24) = 2.261, p = 0.146	F(2, 24) = 26.807, p < 0.001**	F(2, 24) = 0.739, p = 0.488
M3	30	F(1, 24) = 3.702, p = 0.066	F(2, 24) = 22.878, p < 0.001**	F(2, 24) = 0.968, p = 0.394
M4	30	F(1, 24) = 5.232, p = 0.031*	F(2, 24) = 7.803, p = 0.002*	F(2, 24) = 0.067, p = 0.935
M5	29†	F(1, 23) = 7.785, p = 0.010*	F(2, 23) = 2.250, p = 0.128	F(2, 23) = 1.606, p = 0.222

*Significant at 0.05 level
**Significant at 0.005 level
†Missing data

Appendix 12

Two-way (Consonant by jaw) ANOVA results for individuals in the normal-hearing group: Vowel length.

Subject	N	Jaw Effect	Consonant Effect	Consonant x Jaw Interaction
/i/				
F1	30	F(1, 24) = 8.137, p = 0.009*	F(2, 24) = 38.490, p < 0.001**	F(2, 24) = 1.946, p = 0.165
F2	29†	F(1, 23) = 11.130, p = 0.003*	F(2, 23) = 34.110, p < 0.001**	F(2, 23) = 2.415, p = 0.112
F3	30	F(1, 24) = 1.238, p = 0.277	F(2, 24) = 60.940, p < 0.001**	F(2, 24) = 2.681, p = 0.089
F4	30	F(1, 24) = 1.811, p = 0.191	F(2, 24) = 0.365, p = 0.698	F(2, 24) = 0.895, p = 0.698
M1	30	F(1, 24) = 2.598, p = 0.120	F(2, 24) = 45.442, p < 0.001**	F(2, 24) = 0.988, p = 0.387
M2	30	F(1, 24) = 2.703, p = 0.113	F(2, 24) = 22.857, p < 0.001**	F(2, 24) = 0.591, p = 0.561
M3	30	F(1, 24) = 2.294, p = 0.142	F(2, 24) = 23.35, p < 0.001**	F(2, 24) = 0.401, p = 0.674
M4	30	F(1, 24) = 12.05, p = 0.002*	F(2, 24) = 103.26, p < 0.001**	F(2, 24) = 4.014, p = 0.031*
M5	30	F(1, 24) = 4.951, p = 0.036*	F(2, 24) = 121.10, p < 0.001**	F(2, 24) = 6.744, p = 0.005*
/a/				
F1	30	F(1, 24) = 12.926, p < 0.001**	F(2, 24) = 129.40, p < 0.001**	F(2, 24) = 2.860, p = 0.077
F2	29†	F(1, 23) = 8.593, p = 0.008*	F(2, 23) = 170.53, p < 0.001**	F(2, 23) = 2.412, p = 0.112
F3	30	F(1, 24) = 7.239, p = 0.013*	F(2, 24) = 88.14, p < 0.001**	F(2, 24) = 4.843, p = 0.017*
F4	30	F(1, 24) = 148.50, p < 0.001**	F(2, 24) = 430.60, p < 0.001**	F(2, 24) = 29.77, p < 0.001**
M1	30	F(1, 24) = 28.83, p < 0.001**	F(2, 24) = 198.40, p < 0.001**	F(2, 24) = 9.330, p = 0.001*
M2	30	F(1, 24) = 40.04, p < 0.001**	F(2, 24) = 339.60, p < 0.001**	F(2, 24) = 11.30, p < 0.001**
M3	30	F(1, 24) = 3.70, p = 0.066	F(2, 24) = 74.78, p < 0.001**	F(2, 24) = 0.121, p = 0.887
M4	30	F(1, 24) = 5.79, p = 0.024*	F(2, 24) = 218.29, p < 0.001**	F(2, 24) = 2.828, p = 0.079
M5	30	F(1, 24) = 1.14, p = 0.296	F(2, 24) = 143.10, p < 0.001**	F(2, 24) = 7.728, p = 0.003*
/u/				
F1	30	F(1, 24) = 0.61, p = 0.443	F(2, 24) = 25.27, p < 0.001**	F(2, 24) = 0.112, p = 0.895
F2	30	F(1, 24) = 3.96, p = 0.058	F(2, 24) = 42.63, p < 0.001**	F(2, 24) = 8.583, p = 0.002*
F3	30	F(1, 24) = 5.38, p = 0.029*	F(2, 24) = 127.50, p < 0.001**	F(2, 24) = 3.192, p = 0.059
F4	30	F(1, 24) = 22.46, p < 0.001**	F(2, 24) = 60.89, p < 0.001**	F(2, 24) = 2.300, p = 0.122
M1	30	F(1, 24) = 11.41, p = 0.002*	F(2, 24) = 48.92, p < 0.001**	F(2, 24) = 0.665, p = 0.523
M2	30	F(1, 24) = 13.81, p = 0.001*	F(2, 24) = 147.80, p < 0.001**	F(2, 24) = 3.237, p = 0.057
M3	30	F(1, 24) = 25.90, p < 0.001**	F(2, 24) = 104.12, p < 0.001**	F(2, 24) = 0.354, p = 0.705
M4	30	F(1, 24) = 2.74, p = 0.102	F(2, 24) = 46.62, p < 0.001**	F(2, 24) = 0.144, p = 0.867
M5	29†	F(1, 23) = 0.04, p = 0.839	F(2, 23) = 179.17, p < 0.001**	F(2, 23) = 1.557, p = 0.232

*Significant at 0.05 level
**Significant at 0.005 level
†Missing data

Appendix 13

Two-way (Consonant by jaw) ANOVA Results for individuals in the normal-hearing group: Consonant length.

Subject	**N**	**Jaw Effect**	**Consonant Effect**	**Consonant x Jaw Interaction**
/i/				
F1	30	F(1, 24) = 1.723, p = 0.202	F(2, 24) = 157.14, p < 0.001**	F(2, 24) = 1.065, p = 0.361
F2	29†	F(1, 23) = 3.315, p = 0.082	F(1, 23) = 1940.50, p < 0.001**	F(2, 23) = 4.828, p = 0.018*
F3	30	F(1, 24) = 0.003, p = 0.957	F(2, 24) = 67.47, p < 0.001**	F(2, 24) = 0.494, p = 0.616
F4	30	F(1, 24) = 0.382, p = 0.543	F(2, 24) = 636.08, p < 0.001**	F(2, 24) = 0.398, p = 0.676
M1	30	F(1, 24) = 0.711, p = 0.408	F(2, 24) = 275.43, p < 0.001**	F(2, 24) = 0.565, p = 0.576
M2	30	F(1, 24) = 1.058, p = 0.314	F(2, 24) = 45.27, p < 0.001**	F(2, 24) = 0.945, p = 0.403
M3	30	F(1, 24) = 10.076, p = 0.004*	F(2, 24) = 2065.17, p < 0.001**	F(2, 24) = 7.946, p = 0.002*
M4	30	F(1, 24) = 0.012, p = 0.912	F(2, 24) = 110.89, p < 0.001**	F(2, 24) = 4.517, p = 0.022*
M5	30	F(1, 24) = 0.161, p = 0.692	F(2, 24) = 1898.07 p < 0.001**	F(2, 24) = 0.939, p = 0.405
/a/				
F1	30	F(1, 24) = 1.014, p = 0.324	F(2, 24) = 441.65, p < 0.001**	F(2, 24) = 1.901, p = 0.171
F2	29†	F(1, 23) = 4.036, p = 0.056	F(2, 23) = 270.83, p < 0.001**	F(2, 23) = 1.557, p = 0.232
F3	30	F(1, 24) = 0.002, p = 0.963	F(2, 24) = 114.75, p < 0.001**	F(2, 24) = 0.272, p = 0.764
F4	30	F(1, 24) = 15.992, p < 0.001**	F(2, 24) = 1434.59, p < 0.001**	F(2, 24) = 21.946, p < 0.001**
M1	30	F(1, 24) = 8.174, p = 0.009*	F(2, 24) = 235.40, p < 0.001**	F(2, 24) = 9.962, p < 0.001**
M2	30	F(1, 24) = 2.297, p = 0.143	F(2, 24) = 811.82, p < 0.001**	F(2, 24) = 10.830, p < 0.001**
M3	30	F(1, 24) = 1.323, p = 0.261	F(2, 24) = 3.55, p = 0.045*	F(2, 24) = 1.189, p = 0.322
M4	30	F(1, 24) = 32.790, p < 0.001**	F(2, 24) = 875.57, p < 0.001**	F(2, 24) = 47.546, p < 0.001**
M5	30	F(1, 24) = 0.186, p = 0.670	F(2, 24) = 1359.09, p < 0.001**	F(2, 24) = 1.782, p = 0.190
/u/				
F1	30	F(1, 24) = 0.000, p= 1.000	F(2, 24) = 173.06, p < 0.001**	F(2, 24) = 0.141, p = 0.870
F2	30	F(1, 24) = 0.810, p= 0.377	F(2, 24) = 1204.40, p < 0.001**	F(2, 24) = 1.815, p = 0.185
F3	30	F(1, 24) = 0.865, p= 0.362	F(2, 24) = 294.34, p < 0.001**	F(2, 24) = 0.181, p = 0.835
F4	30	F(1, 24) = 0.046, p= 0.832	F(2, 24) = 74.02,0 p < 0.001**	F(2, 24) = 1.646, p = 0.214
M1	30	F(1, 24) = 3.476, p = 0.075	F(2, 24) = 499.195, p < 0.001**	F(2, 24) = 6.752, p = 0.005*
M2	30	F(1, 24) = 0.897, p = 0.353	F(2, 24) = 428.665, p < 0.001**	F(2, 24) = 1.929, p = 0.167
M3	30	F(1, 24) = 1.876, p = 0.184	F(2, 24) = 305.126, p < 0.001**	F(2, 24) = 1.870, p = 0.176
M4	30	F(1, 24) = 7.913, p = 0.010*	F(2, 24) = 453.438, p < 0.001**	F(2, 24) = 14.496, p < 0.001**
M5	29†	F(1, 23) = 0.513, p = 0.481	F(2, 23) = 469/896 p < 0.001**	F(2, 23) = 0.133, p = 0.876

*Significant at 0.05 level
**Significant at 0.005 level
†Missing data

Appendix 14

Two-way (Consonant by jaw) ANOVA Results for individuals in the normal-hearing group: Spectral moment one

Subject	N	Jaw Effect	Consonant Effect	Consonant x Jaw Interaction
/i/				
F1	30	F(1, 24) = 0.179, p = 0.676	F(2, 24) = 11.88, p < 0.001**	F(2, 24) = 1.801, p = 0.187
F2	29†	F(1, 23) = 1.603, p = 0.218	F(2, 23) = 3.64, p = 0.042*	F(2, 23) = 8.356, p = 0.002*
F3	30	F(1, 24) = 2.542, p = 0.124	F(2, 24) = 3.32, p = 0.054	F(2, 24) = 0.006, p = 0.994
F4	30	F(1, 24) = 0.625, p = 0.437	F(2, 24) = 74.39, p < 0.001**	F(2, 24) = 0.003, p = 1.000
M1	30	F(1, 24) = 0.066, p = 0.799	F(2, 24) = 41.71, p < 0.001**	F(2, 24) = 0.483, p = 0.623
M2	30	F(1, 24) = 1.456, p = 0.239	F(2, 24) = 26.73, p < 0.001**	F(2, 24) = 7.939, p = 0.002*
M3	30	F(1, 24) = 4.227, p = 0.051	F(2, 24) = 12.56, p < 0.001**	F(2, 24) = 3.683, p = 0.040*
M4	30	F(1, 24) = 2.141, p = 0.156	F(2, 24) = 0.705, p = 0.504	F(2, 24) = 2.656, p = 0.091
M5	30	F(1, 24) = 1.143, p = 0.296	F(2, 24) = 17.797, p < 0.001**	F(2, 24) = 0.542, p = 0.589
/a/				
F1	30	F(1, 24) = 0.005, p = 0.942	F(2, 24) = 105.800, p < 0.001**	F(2, 24) = 0.558, p = 0.579
F2	29†	F(1, 23) = 0.218, p = 0.645	F(2, 23) = 5.650, p = 0.010*	F(2, 23) = 0.756, p = 0.481
F3	30	F(1, 24) = 3.805, p = 0.063	F(2, 24) = 0.664, p = 0.524	F(2, 24) = 2.951, p = 0.071
F4	30	F(1, 24) = 0.001, p = 0.975	F(2, 24) = 77.922, p < 0.001**	F(2, 24) = 1.867, p = 0.176
M1	30	F(1, 24) = 7.942, p = 0.010*	F(2, 24) = 9.070, p = 0.001*	F(2, 24) = 1.798, p = 0.189
M2	30	F(1, 24) = 7.811, p = 0.010*	F(2, 24) = 56.700, p < 0.001**	F(2, 24) = 10.959, p < 0.001**
M3	30	F(1, 24) = 0.130, p = 0.721	F(2, 24) = 4.294, p = 0.026*	F(2, 24) = 0.725, p = 0.495
M4	30	F(1, 24) = 6.907, p = 0.015*	F(2, 24) = 6.310, p = 0.006*	F(2, 24) = 3.579, p = 0.044*
M5	30	F(1, 24) = 1.397, p = 0.249	F(2, 24) = 78.318, p < 0.001**	F(2, 24) = 0.964, p = 0.395
/u/				
F1	30	F(1, 24) = 0.960, p = 0.337	F(2, 24) = 25.670, p < 0.001**	F(2, 24) = 0.695, p = 0.509
F2	30	F(1, 24) = 1.115, p = 0.738	F(2, 24) = 3.047, p = 0.066	F(2, 24) = 1.273, p = 0.298
F3	30	F(1, 24) = 0.764, p = 0.391	F(2, 24) = 9.071, p = 0.001*	F(2, 24) = 0.667, p = 0.522
F4	30	F(1, 24) = 5.990, p = 0.022*	F(2, 24) = 21.610, p < 0.001**	F(2, 24) = 1.805, p = 0.186
M1	30	F(1, 24) = 0.084, p = 0.775	F(2, 24) = 4.449, p = 0.023*	F(2, 24) = 0.297, p = 0.746
M2	30	F(1, 24) = 23.34, p < 0.001**	F(2, 24) = 38.72, p < 0.001**	F(2, 24) = 12.34, p < 0.001**
M3	30	F(1, 24) = 1.85, p = 0.187	F(2, 24) = 10.38, p < 0.001**	F(2, 24) = 0.511, p = 0.607
M4	30	F(1, 24) = 0.254, p = 0.619	F(2, 24) = 5.194, p = 0.013*	F(2, 24) = 1.614, p = 0.220
M5	29†	F(1, 23) = 0.416, p = 0.840	F(2, 23) = 6.928, p = 0.004*	F(2, 23) = 1.666, p = 0.211

*Significant at 0.05 level
**Significant at 0.005 level
†Missing data

Appendix 15

Two-way (Consonant by jaw) ANOVA Results for individuals in the normal-hearing group: Spectral moment two

Subject	N	Jaw Effect	Consonant Effect	Consonant x Jaw Interaction
/i/				
F1	30	$F(1, 24) = 0.214, p = 0.648$	$F(2, 24) = 20.074, p < 0.001$**	$F(2, 24) = 4.080, p = 0.030$*
F2	29†	$F(1, 23) = 0.017, p = 0.896$	$F(2, 23) = 57.027, p < 0.001$**	$F(2, 23) = 0.763, p = 0.478$
F3	30	$F(1, 24) = 0.150, p = 0.702$	$F(2, 24) = 45.809, p < 0.001$**	$F(2, 24) = 0.443, p = 0.647$
F4	30	$F(1, 24) = 0.003, p = 0.955$	$F(2, 24) = 186.120, p < 0.001$**	$F(2, 24) = 0.559, p = 0.579$
M1	30	$F(1, 24) = 0.972, p = 0.334$	$F(2, 24) = 44.892, p < 0.001$**	$F(2, 24) = 1.204, p = 0.318$
M2	30	$F(1, 24) = 10.78, p = 0.003$*	$F(2, 24) = 75.293, p < 0.001$**	$F(2, 24) = 4.984, p = 0.015$*
M3	30	$F(1, 24) = 0.003, p = 0.987$	$F(2, 24) = 24.797, p < 0.001$**	$F(2, 24) = 0.176, p = 0.840$
M4	30	$F(1, 24) = 1.962, p = 0.174$	$F(2, 24) = 106.530, p < 0.001$**	$F(2, 24) = 0.540, p = 0.590$
M5	30	$F(1, 24) = 0.197, p = 0.661$	$F(2, 24) = 140.913, p < 0.001$**	$F(2, 24) = 0.642, p = 0.535$
/a/				
F1	30	$F(1, 24) = 0.328, p = 0.572$	$F(2, 24) = 13.500, p < 0.001$**	$F(2, 24) = 0.474, p = 0.629$
F2	29 †	$F(1, 23) = 0.376, p = 0.546$	$F(2, 23) = 65.289, p < 0.001$**	$F(2, 23) = 1.286, p = 0.296$
F3	30	$F(1, 24) = 0.846, p = 0.367$	$F(2, 24) = 29.431, p < 0.001$**	$F(2, 24) = 0.938, p = 0.405$
F4	30	$F(1, 24) = 0.529, p = 0.474$	$F(2, 24) = 47.118, p < 0.001$**	$F(2, 24) = 3.129, p = 0.062$
M1	30	$F(1, 24) = 1.057, p = 0.315$	$F(2, 24) = 87.080, p < 0.001$**	$F(2, 24) = 6.690, p = 0.005$*
M2	30	$F(1, 24) = 60.002, p < 0.001$**	$F(2, 24) = 60.252, p < 0.001$**	$F(2, 24) = 13.916, p < 0.001$**
M3	30	$F(1, 24) = 1.090, p = 0.307$	$F(2, 24) = 19.652, p < 0.001$**	$F(2, 24) = 0.995, p = 0.385$
M4	30	$F(1, 24) = 0.186, p = 0.670$	$F(2, 24) = 67.122, p < 0.001$**	$F(2, 24) = 1.624, p = 0.218$
M5	30	$F(1, 24) = 0.069, p = 0.795$	$F(2, 24) = 26.110, p < 0.001$**	$F(2, 24) = 0.945, p = 0.403$
/u/				
F1	30	$F(1, 24) = 0.042, p = 0.840$	$F(2, 24) = 22.455, p < 0.001$**	$F(2, 24) = 3.208, p = 0.058$
F2	30	$F(1, 24) = 1.526, p = 0.229$	$F(2, 24) = 50.112, p < 0.001$**	$F(2, 24) = 4.508, p = 0.022$*
F3	30	$F(1, 24) = 0.279, p = 0.602$	$F(2, 24) = 58.714, p < 0.001$**	$F(2, 24) = 0.210, p = 0.812$
F4	30	$F(1, 24) = 0.004, p = 0.949$	$F(2, 24) = 45.031, p < 0.001$**	$F(2, 24) = 1.562, p = 0.230$
M1	30	$F(1, 24) = 0.073, p = 0.790$	$F(2, 24) = 37.693, p < 0.001$**	$F(2, 24) = 0.561, p = 0.578$
M2	30	$F(1, 24) = 10.155, p = 0.004$*	$F(2, 23) = 108.150, p < 0.001$**	$F(2, 24) = 0.487, p = 0.621$
M3	30	$F(1, 24) = 1.870, p = 0.184$	$F(2, 24) = 77.708, p < 0.001$**	$F(2, 24) = 0.466, p = 0.633$
M4	30	$F(1, 24) = 0.511, p = 0.482$	$F(2, 24) = 35.439, p < 0.001$**	$F(2, 24) = 0.002, p = 0.998$
M5	29†	$F(1, 23) = 1.379, p = 0.252$	$F(2, 23) = 259.073, p < 0.001$**	$F(2, 23) = 0.535, p = 0.593$

*Significant at 0.05 level
**Significant at 0.005 level
†Missing data

Appendix 16

Two-way (Consonant by jaw) ANOVA Results for individuals in the normal-hearing group: Open quotient

Subject	N	Jaw Effect	Consonant Effect	Consonant x Jaw Interaction
/i/				
F1		---	---	---
F2	14†	F(1, 8) = 2.331, p = 0.165	F(2, 8) = 1.187, p = 0.354	F(2, 24) = 0.626, p = 0.559
F3		---	---	---
F4		---	---	---
M1	14†	F(1, 10) = 3.119, p = 0.108	F(2, 10) = 0.0901, p = 0.915	---
M2	23†	F(1, 17) = 5.399, p = 0.033*	F(2, 24) = 0.4260, p = 0.958	F(2, 24) = 0.039, p = 0.961
M3	19†	F(1, 13) = 0.136, p = 0.718	F(2, 13) = 0.971, p = 0.405	F(2, 13) = 0.753, p = 0.491
M4	20†	F(1, 14) = 1.523, p = 0.238	F(2, 14) = 2.903, p = 0.088	F(2, 14) = 1.903, p = 0.186
M5	29†	F(1, 23) = 3.832, p = 0.063	F(2, 23) = 0.265, p = 0.770	F(2, 23) = 1.408, p = 0.265
/a/				
F1		---	---	---
F2	9†	F(1, 5) = 0.0672, p = 0.806	F(2, 5) = 0.556, p = 0.605	---
F3		---	---	---
F4		---	---	---
M1		---	---	---
M2	22†	F(1, 16) = 3.254, p = 0.090	F(2, 16) = 1.023, p = 0.382	F(2, 16) = 1.297, p = 0.301
M3	14†	F(1, 10) = 0.197, p = 0.666	F(2, 10) = 1.128, p = 0.362	---
M4	18†	F(1, 12) = 0.723, p = 0.412	F(2, 12) = 0.917, p = 0.426	F(2, 12) = 0.011, p = 0.989
M5	29†	F(1, 23) = 7.170, p = 0.013*	F(2, 23) = 2.316, p = 0.121	F(2, 23) = 3.620, p = 0.043*
/u/				
F1		---	---	---
F2	26†	F(1, 20) = 3.6620, p = 0.070	F(2, 20) = 1.15, p = 0.338	F(2, 20) = 4.458, p = 0.025*
F3	5†	F(1, 24) = 5.4440, p = 0.258	F(2, 24) = 6.83, p = 0.261	---
F4		---	---	---
M1		---	---	---
M2	15†	F(1, 9) = 2.4660, p = 0.151	F(2, 9) = 3.425, p = 0.078	F(2, 9) = 0.0904, p = 0.914
M3	14†	F(1, 10) = 0.0008, p = 0.979	F(2, 10) = 3.796, p = 0.059	---
M4		---	---	---
M5	24†	F(1, 18) = 2.6270, p = 0.122	F(2, 18) = 1.477, p = 0.255	F(1, 18) = 0.5350, p = 0.595

*Significant at 0.05 level
**Significant at 0.005 level
†Missing data

Appendix 17

Two-way (Consonant by jaw) ANOVA Results for individuals in the normal-hearing group: Speed quotient

Subject	**N**	**Jaw Effect**	**Consonant Effect**	**Consonant x Jaw Interaction**
/i/				
F1		---	---	---
F2	14[†]	F(1, 8) = 1.585, p = 0.244	F(2, 8) = 0.470, p = 0.641	F(2, 8) = 0.358, p = 0.710
F3		---	---	---
F4		---	---	---
M1	14[†]	F(1, 10) = 3.286, p = 0.100	F(2, 10) = 0.161, p = 0.854	---
M2	23[†]	F(1, 17) = 3.926, p = 0.064	F(2, 17) = 0.293, p = 0.749	F(2, 17) = 0.054, p = 0.947
M3	19[†]	F(1, 13) = 0.128, p = 0.727	F(2, 13) = 0.301, p = 0.745	F(2, 13) = 0.335, p = 0.721
M4	20[†]	F(1, 14) = 2.079, p = 0.171	F(2, 14) = 3.781, p = 0.049*	F(2, 14) = 1.529, p = 0.251
M5	29[†]	F(1, 23) = 2.216, p = 0.150	F(2, 23) = 1.217, p = 0.314	F(2, 23) = 1.133, p = 0.340
/a/				
F1		---	---	---
F2	9[†]	F(1, 5) = 0.0017, p = 0.968	F(2, 5) = 0.026, p = 0.974	---
F3		---	---	---
F4		---	---	---
M1	30	F(1, 24) = 0.759, p = 0.392	F(2, 24) = 13.988, p < 0.001**	F(2, 24) = 0.385, p = 0.685
M2	22[†]	F(1, 16) = 2.362, p = 0.144	F(2, 16) = 1.131, p = 0.347	F(2, 16) = 1.431, p = 0.268
M3	14[†]	F(1, 10) = 0.261, p = 0.620	F(2, 10) = 1.532, p = 0.263	---
M4	18[†]	F(1, 12) = 0.626, p = 0.444	F(2, 12) = 0.666, p = 0.532	F(2, 12) = 0.021, p = 0.979
M5	29[†]	F(1, 23) = 4.976, p = 0.036*	F(2, 23) = 2.278, p = 0.125	F(2, 23) = 2.751, p = 0.085
/u/				
F1		---	---	---
F2	26[†]	F(1, 20) = 3.487, p = 0.077	F(2, 20) = 1.749, p = 0.200	F(2, 20) = 3.105, p = 0.067
F3	5[†]	F(1, 1) = 4.000, p = 0.295	F(2, 1) = 2.688, p = 0.396	---
F4		---	---	---
M1		---	---	---
M2	15[†]	F(1, 9) = 0.001, p = 0.973	F(2, 9) = 0.253, p = 0.782	F(2, 9) = 1.889, p = 0.207
M3	14[†]	F(1, 10) = 0.154, p = 0.703	F(2, 10) = 2.808, p = 0.108	---
M4		---	---	---
M5	24[†]	F(1, 18) = 1.680, p = 0.211	F(2, 18) = 2.328, p = 0.126	F(2, 18) = 0.045, p = 0.956

*Significant at 0.05 level
**Significant at 0.005 level
[†]Missing data

Appendix 18

Two-way (Consonant by jaw) ANOVA Results for individuals in the normal-hearing group: Jaw displacement

Subject	N	Jaw Effect	Consonant Effect	Consonant x Jaw Interaction
/i/				
F1	30	F(1, 24) = 0.903, p = 0.351	F(2, 24) = 7.069, p = 0.004*	F(2, 24) = 0.485, p = 0.622
F2	19†	F(1, 13) = 10.840, p = 0.006*	F(2, 13) = 1.268, p = 0.314	F(2, 13) = 0.070, p = 0.933
F3	30	F(1, 24) = 1.370, p = 0.254	F(2, 24) = 2.059, p = 0.151	F(2, 24) = 1.162, p = 0.331
F4	30	F(1, 24) = 0.838, p = 0.369	F(2, 24) = 4.241, p = 0.026*	F(2, 24) = 2.361, p = 0.116
M1	30	F(1, 24) = 16.322, p < 0.001**	F(2, 24) = 2.126, p = 0.142	F(2, 24) = 0.975, p = 0.392
M2	30	F(1, 24) = 0.894, p = 0.355	F(2, 24) = 1.695, p = 0.207	F(2, 24) = 3.482, p = 0.049*
M3	30	F(1, 24) = 8.117, p = 0.009*	F(2, 24) = 3.177, p = 0.060*	F(2, 24) = 0.080, p = 0.923
M4	30	F(1, 24) = 7.131, p = 0.013*	F(2, 24) = 0.714, p = 0.500	F(2, 24) = 0.803, p = 0.460
M5	30	F(1, 24) = 2.960, p = 0.098	F(2, 24) = 2.647, p = 0.091	F(2, 24) = 1.170, p = 0.327
/a/				
F1	30	F(1, 24) = 28.542, p < 0.001**	F(2, 24) = 2.796, p = 0.081	F(2, 24) = 2.631, p = 0.093
F2	28†	F(1, 22) = 0.109, p = 0.744	F(2, 22) = 2.748, p = 0.086	F(2, 22) = 0.244, p = 0.785
F3	30	F(1, 24) = 13.506, p < 0.001**	F(2, 24) = 8.865, p < 0.001**	F(2, 24) = 1.646, p = 0.214
F4	30	F(1, 24) = 15.998, p < 0.001**	F(2, 24) = 42.040, p < 0.001**	F(2, 24) = 5.880, p = 0.008*
M1	30	F(1, 24) = 0.712, p = 0.407	F(2, 24) = 10.249, p < 0.001**	F(2, 24) = 1.100, p = 0.349
M2	29†	F(1, 23) = 71.344, p < 0.001**	F(2, 23) = 33.314, p < 0.001**	F(2, 23) = 9.266, p = 0.001*
M3	30	F(1, 24) = 1.118, p = 0.302	F(2, 24) = 18.812, p < 0.001**	F(2, 24) = 0.826, p = 0.451
M4	30	F(1, 24) = 0.688, p = 0.417	F(2, 24) = 6.642, p = 0.006*	F(2, 24) = 1.144, p = 0.339
M5	30	F(1, 24) = 10.114, p = 0.004*	F(2, 24) = 30.275, p < 0.001**	F(2, 24) = 5.557, p = 0.010*
/u/				
F1	30	F(1, 24) = 0.002, p = 0.968	F(2, 24) = 3.814, p = 0.036*	F(2, 24) = 6.692, p = 0.005*
F2	29†	F(1, 23) = 12.997, p = 0.001*	F(2, 23) = 5.963, p = 0.008*	F(2, 23) = 2.011, p = 0.157
F3	30	F(1, 24) = 1.937, p = 0.178	F(2, 24) = 0.141, p = 0.869	F(2, 24) = 7.652, p = 0.003*
F4	30	F(1, 24) = 0.040, p = 0.841	F(2, 24) = 41.012, p < 0.001**	F(2, 24) = 1.059, p = 0.362
M1	30	F(1, 24) = 1.704, p = 0.205	F(2, 24) = 1.110, p = 0.347	F(2, 24) = 0.397, p = 0.677
M2	30	F(1, 24) = 4.010, p = 0.058	F(2, 24) = 1.014, p = 0.379	F(2, 24) = 0.326, p = 0.725
M3	30	F(1, 24) = 4.292, p = 0.049*	F(2, 24) = 0.531, p = 0.595	F(2, 24) = 0.111, p = 0.896
M4	21†	F(1, 15) = 2.386, p = 0.143	F(2, 15) = 1.208, p = 0.326	F(2, 15) = 2.001, p = 0.170
M5	29†	F(1, 23) = 0.235, p = 0.632	F(2, 23) = 1.100, p = 0.350	F(2, 23) = 2.670, p = 0.091

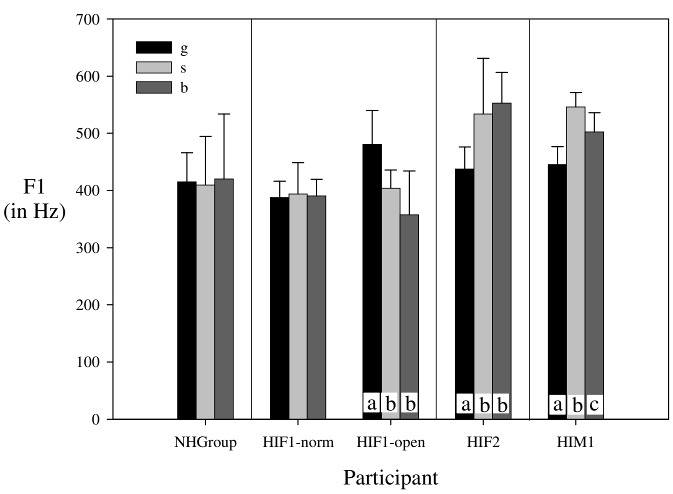
*Significant at 0.05 level
**Significant at 0.005 level
†Missing data

Appendix 19

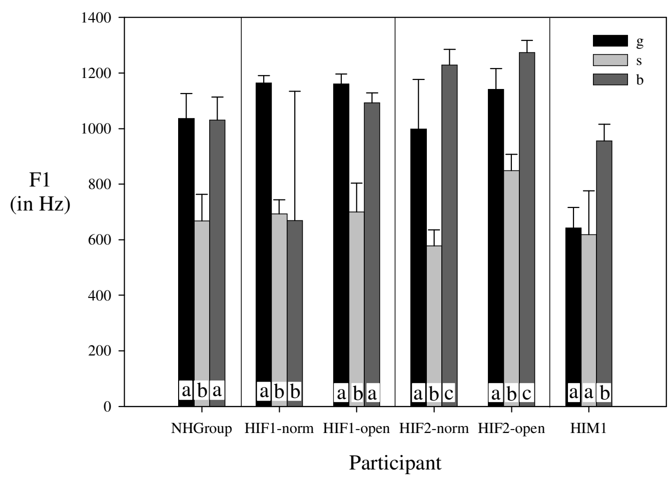
Consonant Effect on F1:

Means and standard deviations of F1 for each of the three vowels /i, a, u/ in the three consonant (/g, s, b/) contexts for the normal-hearing group (NHGroup) and the three hearing-impaired participants (HIF1, HIF2, HIM1). Data showing a significant consonant and jaw interaction effect were presented in the normal ("norm") and open jaw ("open") conditions separately. Significantly different pairs in each data set were marked with different letters.

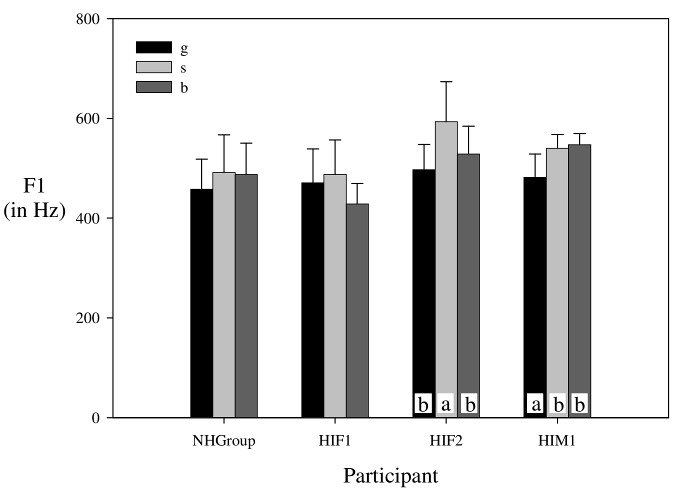
Appendix. 20.1 Vowel /i/



Appendix. 20.2 Vowel /a/



Appendix. 20.3 Vowel /u/

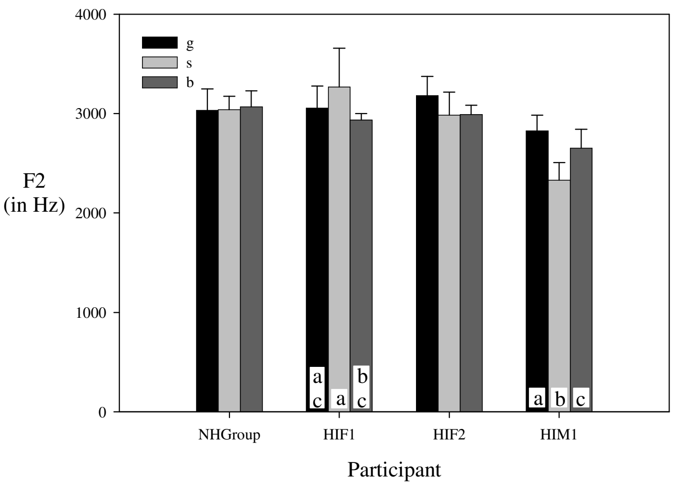


Appendix 20

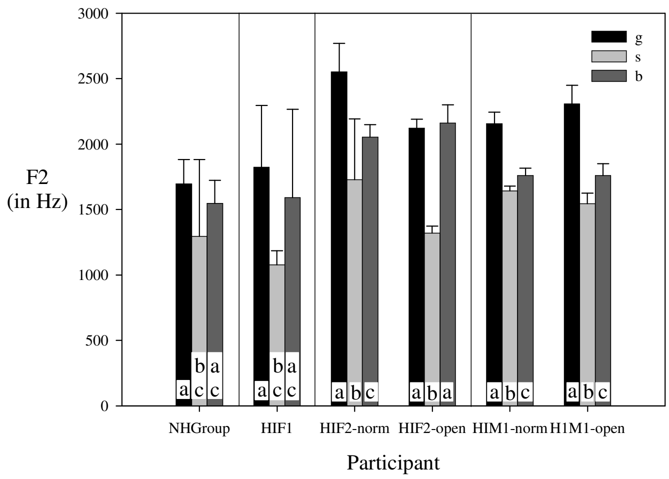
Consonant Effect on F2:

Means and standard deviations of F2 for each of the three vowels /i, a, u/ in the three consonant (/g, s, b/) contexts for the normal-hearing group (NHGroup) and the three hearing-impaired participants (HIF1, HIF2, HIM1). Data showing a significant consonant and jaw interaction effect were presented in the normal ("norm") and open jaw ("open") conditions separately. Significantly different pairs in each data set were marked with different letters.

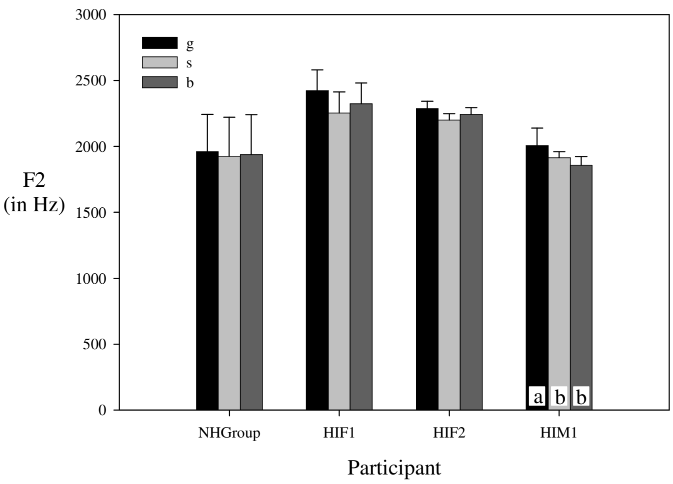
Appendix. 22.1 Vowel /i/



Appendix. 21.2 Vowel /a/



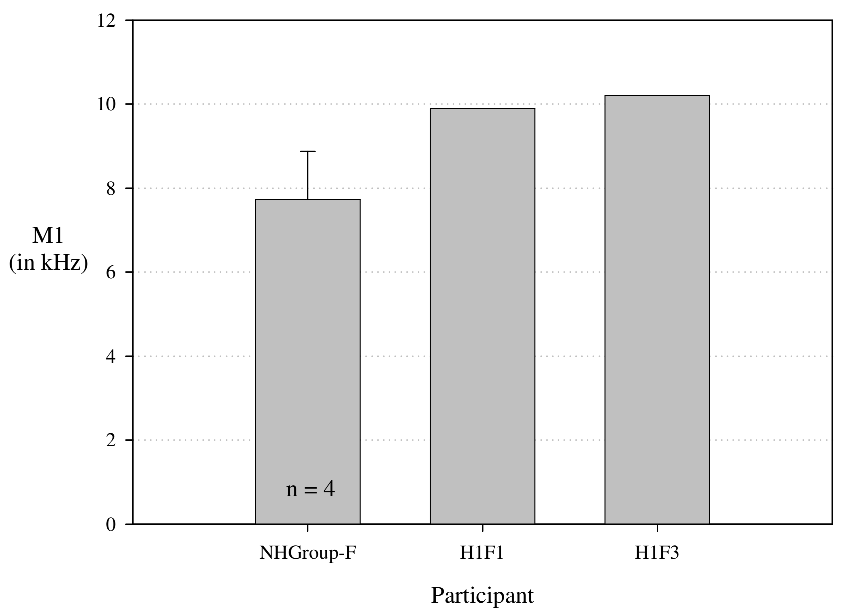
Appendix. 21.3 Vowel /u/

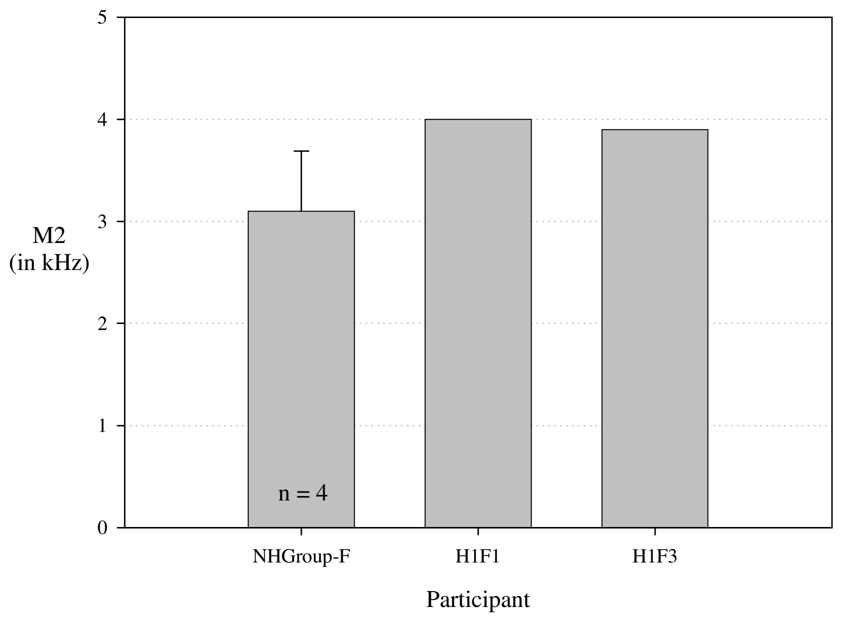


Appendix 21

Spectral Moments for the correctly articulated and misarticulated /d/

Means and standard deviations of M1 (upper graph) and M2 (lower graph) measured from the /d/ consonant correctly produced by the normal-hearing females (NHGroup-F) and misarticulated by H1F1 (misarticulated as /t/) and H1F3 (misarticulated as /s/).





Appendix 22

Spectral Moments for the correctly articulated and misarticulated /s/

Means and standard deviations of M1 (upper graph) and M2 (lower graph) measured from the /s/ consonant correctly produced by the normal-hearing females (NHGroup-F) and males (NHGroup-M) and misarticulated by H1F3 (misarticulated as /sh/) and H1M1 (misarticulated as /th/).