Derived Measures of Vowel Acoustics in Children with Hearing Impairment: A Systematic Review

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19SLP009

This Dissertation is submitted as part

fulfilment for the Degree of Master of Science in Speech Language Pathology

University of Mysore, Mysuru

ALL INDIA INSTITUTE OF SPEECH AND HEARING

Manasagangothri, Mysuru 570 006

September, 2021

Dedicated to my parents

CERTIFICATE

This is to certify that this dissertation entitled **‘Derived Measures of Vowel Acoustics in Children with Hearing Impairment: A systematic Review’** is a bonafide work submitted as a part for the fulfilment for the degree of Master of Science (Speech Language Pathology) of the student Registration Number: 19SLP009. This has been carried out under the guidance of the faculty of this institute and has not been submitted earlier to any other University for the award of any other Diploma or Degree.

Mysuru
September 2021

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DECLARATION

This is to certify that this dissertation entitled **‘Derived Measures of Vowel Acoustics in Children with Hearing Impairment: A systematic Review’** is the result of my own study under the guidance of Dr. N. Sreedevi, Professor & Head, Department of Prevention of Communication Disorders, All India Institute of Speech and Hearing, Mysore and has not been submitted earlier to any other University for the award of any other Diploma or Degree

Mysuru	**Registration Number:**
September 2021	**19SLP009**

ACKNOWLEDGMENTS

I would like to express my sincere thanks to my guide, ***Prof. N. Sreedevi****, for the constant support and guidance. Without you this study would not have been possible madam. Your patience, ever smiling face, dedication to the work, and guidance in the research motivated me to carry out this study. Your presence always made me feel I am with my mother. Thanks for inspiring hope in me, igniting my imagination, and instilling in me – a love of learning.*

I would like to express my sincere thanks to **Prof. M Pushpavathi, Director, AIISH** *for letting me carry out this study***.**

I would like to remember and thank, ***Dr. Abhishek B P sir****, for his inspiring personality that made me get into research in the field of SLP.*

I would like to thank my best buddies **Prabuddha, Dilli, Prateek, Anshuman and Ankit** *for all the beautiful memories at AIISH. I really can't imagine my college and hostel life without them. I cherish each and every moment spent with them.*

I would like to thank my dear ***Sajana,*** *love of my life***,** *without your help and support, wouldn't have completed my dissertation. You stand like a backbone for me always, ready to help anything and return my tempo when I lose it.*

A special thanks to my seniors ***Prateek dai, Sushil dai, Narayan dai, Ranjit dai, Aashish dai, Sabin dai, Dibya didi*** *and* ***Kranti didi*** *who always helped me during my Bsc. and throughout journey of Msc and also,* **Prativa** *and* **Parbati** *my classmates at IOM who are close to me always.*

I would like to thank my classmates **Shraddha, Abhishek, Chethan, Madhu and Bandhan,** *for always being there for me***.** *Last but not the least, Renovators 2.0, which includes some of the best company I had alongside with me in my entire journey in AIISH.*

I also would like to thank my dissertation partners, ***Anima and Arva****, for being such a good companion throughout.*

I thank to ***Shashish bhai,*** *for always patiently listening my words and helping me throughout. I wish you all the best.*

I would like to thank all staff of ***AIISH, my seniors, juniors****, who have helped me directly or indirectly to gain knowledge.*

I thank my family for supporting me in every situation and decisions taken. ***Mummy Buwa, my brother Iraj and Sister-in law Jharana*** *you'll always be in my heart.*

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Chapter 1

Introduction

Humans are gifted with speech and language to express their needs. They have a capacity to communicate through the mode of speech and language, and it is a primary mode of communication in humans. Speech is the process where language is expressed orally. It constitutes various components within it, including voicing, fluency, articulation, resonance, and prosody. Kent and Read (2002) define speech as an acoustic-vocal channel that has rapid fading transmission and is capable of transmission of meaning with the use of an arbitrary set of symbols. In simple words, speech can be considered as a phenomenon of converting energy from one source to energy in other sources, i.e., speech is basically the conversion of energy from the respiratory system by vocal folds which is further modified by the structures in the vocal tract to give a distinct shape (different class of speech sounds).

Speech sounds include consonants and vowels. There exists a difference in the production of these speech sounds. Consonants are produced with some constrictions in the vocal tract, while vowels are produced with relatively open vocal tract configuration (Ladefoged & Maddieson, 1996). Vowels are produced with various vocal tract shapes and further varied with articulators' positions, which makes it different from the consonants. Due to changes in the vocal tract configuration, the net acoustic energy present in one vocal tract configuration is different from the other. This results in the perception of various types of vowels, i.e., front vowel or back vowel, high vowel or low vowel, rounded vowel or unrounded vowel. Acoustically, vowels are classified/differentiated into various types based on the formant frequencies, spectrum, shape of the vocal tract, and duration (Fant,1960). With these several cues, humans are capable of differentiating the classes of sounds (vowels versus consonants), and within each class, like vowels, different types of vowels (high vs. low, front vs. back, rounded vs. unrounded).

Hearing is the major route of perceiving oral communication. As soon as a child is born, he/she starts to use his/her aural route to perceive, process, and comprehend human speech and language and other environmental sounds (Whetnall & Fry, 1964). Hence, hearing is special to humans that helps one to perceive human speech and language. But there are various prenatal, perinatal and postnatal conditions that lead to alterations in the normal hearing mechanism causing hearing impairment. Therefore, hearing impairment (HI) could be considered congenital or acquired depending upon the onset of the conditions. It varies from mild to profound hearing impairment, depending upon the severity.

Any alterations, either congenital or acquired or mild or profound deficit in hearing, can have an evident effect on both speech perception and speech production. Children with hearing impairment do exhibit speech with reduced intelligibility. This is due to errors during the articulation of speech sounds. The extent of errors depends on the onset, type, or severity of hearing impairment (Abraham et al., 2019).

Children with HI tend to show errors in the production of both consonants and vowels. Place of articulation is mostly affected during consonant production, and clusters are affected most with either omission of the cluster or simplification via insertion of schwa vowel (Baudonck et al., 2010). Similarly, vowels also tend to be disrupted in the quality of articulation. HI children tend to produce vowels with substitution errors. Back vowels are more easily produced as compared to front vowels. In the mean-time, vowels articulated with closed vocal tract has been observed to be more affected compared to vowels articulated with open vocal tract (Smith. 1975; Geffner,1980; Ozbic & Kogovsek, 2010; Stein, 1981; Markides, 1970). Literature reports neutralization of vowels, diphthongization, and nasalization of vowels tend to be well-known errors among HI children (Stevens et al., 1976). These findings in the errors have been objectively studied or measured via various formant studies.

On comparison of speech of children with hearing-impairment with typically developing children, the formant pattern between them has distinct variations. An acoustical analysis is used for measuring these variations in formant patterns. It gives qualitative results to assess formant patterns and, compare and contrast the severity of the disorder. This helps one to develop assessment guidelines and also to look into the benefit of speech therapy intervention.

Vowel formant frequencies are frequently used in the study of vowel production through acoustic analysis. The first two formants, i.e., first formant (F1) and second formant (F2), have been used to study the tongue position within the range of frequency in a specific person. Hence, acoustic measures could be an option to extract the nature of vowel articulation in individuals where direct physiological assessment is not feasible (Karlsson & Van Doorn, 2012). F1 and F2 have been studied on the fact that they are important to predict the position of the tongue during the vowel production. And this tongue position can be varied among the speaker, meaning it is specific for a specific speaker. When F1 and F2 are used to plot the F2-F1 plane for corner vowels, namely /a/,

/i/, and /u/, a potential space is obtained between these plots, and the size of the space gives the articulatory precision for the person. This potential space among the corner vowels is termed as Vowel Space Area (VSA) (Turner et al., 1995; Bradlow et al.1996). VSA can be derived by either use of three or four vowel systems. If three vowels are used, then it is termed as VSA3 and VSA4 if four vowels are used. These measurement metrics have formed bases for many studies and have been used to look into the reduction in articulation in individual with hearing impairment. But however, the findings from VSA metrics have failed many a time to predict the articulatory reduction even when there is a consistent difference in articulation in hearing-impaired children. (Liu et al., 2005; Roy et al., 2009; Sapir et al., 2010; Skodda et al., 2012; Turner et al., 1995; Weismer et al.,2000.; Zlegler et al.,1983.; Zupan, 2002)

Since VSA metrics had contradicting results, there were attempts to develop other means of measuring vowel acoustics. A reorganization of formant frequency has been proposed named Formant Centralization Ratio (FCR) in this attempt. FCR is obtained through the quotient of formant frequency sums. Here, the mathematical form is such a way developed or has been given that "the formant frequencies in the numerator are likely to increase, and the formant frequencies in the denominator are likely to decrease with vowel centralization"(Sapir et al., 2010). FCR for three vowel system vowel space area has been defined as follows:

$$FCR= (F2u + F2a + F1i + F1u)/ (F2i + F1a) \qquad \text{equation (1)}$$

Also, $FCR = 1/ VAI3$

where the F (formant values) in each equation correspond to the F1 and F2 measurements of the vowels /i, a, u/ (subscripts). As indicated in Eqn. 1, the FCR is the inverse of an alternative measure, the Vowel Articulation Index (VAI), proposed by Roy et al.(2009) for the same number of vowels. In case of the VAI measure, a four-vowel variant, is defined as

$$VAI4 = (F2i + F2æ + F1æ + F1a)/ (F1i + F1u + F2u + F2a)$$

The VAI is a new acoustic metric of vowel formant production, designed to minimize the effects of inter-speaker variability and maximize sensitivity to formant centralization (Sapir et al., 2009; Sapir et al., 2010). It has been shown that inter-speaker variability can be considerably reduced by using speaker normalization procedures such as extrinsic vowel information, formant intrinsic information, and formant ratios (Adank et al., 2004; Gopal, 1986). These normalization procedures include ‘‘intrinsic’’ methods, which are based on relationships among all steady-state properties (F0, F1, F2, F3) of individual vowel tokens, and ‘‘extrinsic’’ methods, which involve the relationships among the formant frequencies of the entire vowel system of a speaker (Ainsworth et al., 1974). A sensitive acoustic index of normal and abnormal vowel articulation should probably include these features: vowel extrinsic, formant intrinsic, a ratio, and an arrangement of the vowel-formant elements in such a way that the ratio is maximally sensitive to vowel centralization and decentralization (Sapir et. al, 2009a; Sapir et al., 2010).

Another alternative approach has also been studied to look into the estimated articulatory range in speakers to analyze other aspects of vowel space size. One such parameter includes: Average Vowel Spacing (AVS) metric, proposed by Laane et al. (2001) and is defined as the procedure of forming the pairwise Euclidean distances (ED) between F1 and F2 frequencies of corner vowels (indexed by vowel /i/) which is subsequently averaged to form a single separation quantity for the full set of *n* vowels (Skodda et al., 2011). Euclidean distance (ED) or straight-line distance is one of the ways of quantifying vowel space expansion between a vowel and the center of the vowel space. AVS is calculated using the following equation:

$$\text{AVS:} \quad \frac{2}{n(n-1)} \left\{ \sum_{i=1}^{n-1} \sum_{j=j+1}^{n} \sqrt{(F_{1_i} - F_{1j})^2 + (F_{2_i} - F_{2j})^2} \right\}$$

The AVS is predicted to increase in an expanding vowel space articulation and to decrease in reduced articulation range (Lane et al., 2001). A metric similar to the AVS was also shown to be more powerful than VSA in the prediction of speech intelligibility, affirming that distance-based metrics may offer advantages over those estimating overall acoustic area (Neel et al. 2008). These findings are consistent with the studies by Bradlow et al. (1996) who investigated the Euclidian distance by slightly changing the AVS equation by Laane et al. (2001).

Euclidean Distance (ED), or the straight-line distance between vowel and the center of vowel space, is one of the methods to quantify vowel (Neumeyer et al., 2010b). Euclidean Distance (ED), Vowel Space Length (VSL) and Acoustic Distance (AD), difference between two formant values from the center of vowel space and measured in Hz, are used interchangeably (Neumeyer et al., 2010b; Yang et al., 2015a; Yang & Xu, 2017) . In order to quantitatively describe the extent to which the vowel acoustic features between typically developing (TD) and hearing impaired differ, a measure of acoustic distance (AD) was derived on the basis of rescaled normalized formant values (Yang et al., 2015a). First, for each vowel, the mean F1 and F2 are calculated across all the TD children. These values serve as the TD target formant frequency values. Next, the Euclidean distance between each hearing impaired and TD child's vowel production and the corresponding TD target is calculated using the formula.

$$\mathrm{AD}_{jk} = \sqrt{(\mathrm{F1}_{jk} - \mathrm{F1}'_{\ j})^2 + (\mathrm{F2}_{jk} - \mathrm{F2}'_{\ j})^2},$$

Where $F1_j$ is the group means of F1 for all TD children for vowel *j* (either vowel /a/, /i / or /u/) and $F1_{jk}$ is the mean F1 of vowel *j* for the kth subject. $F2_j$ is the group mean of F2 for all TD children for vowel j, and $F2_{jk}$ is the mean F2 of vowel j for the kth subject.

While measuring ED, instead of representing vowels in the formant plane with a single static slice extracted at the vowel target, methodology suggested by Watson and Harrington (1999) and Harrington et al. (2008) is used through parameterizing the entire shape of the (Bark-scaled) vowel formant as a function of time, thereby preserving dynamic information. For this, each formant trajectory is minimized to a point in a three-parameter space using the Discrete Cosine Transformation (DCT) (Watson & Harrington, 1999). This technique decomposes any digital signal into a set of 1/2 cycle cosine waves which, if summed, reconstructs the original signal entirely.

Number of derived measures are used in the analysis of vowel production in children with hearing impairment. There are subtle differences among the various measures of vowel acoustics. Abundant literature have been reported from western countries (Kent & Vorperian, 2018b). However, reports from Asian countries like India have not gained much of attention in the field speech sciences globally, despite having good resources and manpower. Professionals like engineers, linguists and medical physicist have good scope in the field of speech acoustics. Also, they have been frequently involved in development of speech-based applications (mostly AAC apps) for communication disorders. Therefore, compilation of the works done in the field of vowel acoustics within Asian countries is essential. Moreover, findings in derived measures of vowel acoustics are found to be different among children with hearing impairment when compared to typically developing children (Kent & Vorperian, 2018b). Also, these measures have been successfully used in profiling articulation characteristic pre and post intervention (Eliasova et al., 2013; Lin et al., 2012; Mahler & Ramig, 2012; Pettinato et al., 2016a; Roy et al., 2009; Sapir et al., 2007; Takatsu et al., 2017; Wenke et al., 2010). Derived measures are used to develop various normative values for typically developing children, and also for adults. These norms can be a good source for comparing speech of disordered population with normal. Also, these measures give physiological data that helps us to look into whether one has normal physiology of speech sound development or not. Hence, there is necessity of compiling reports available in various language across countries in the Asian continent, so that researchers/clinicians in the field of speech science can critically evaluate the best methods available and further incorporate them in their clinical practice.

1.1 Need for the study

Speech sounds are produced when sounds from vocal folds are modified by the articulators in the vocal tract. Vowels are such class of speech sounds produced with relatively open vocal tract configuration, and has major contribution in speech intelligibility. However, there occurs change in net acoustic energy due to various vocal tract configuration, this might not be appreciated when there is deprivation in hearing. Due to this lack of sensitivity of hearing in children with hearing impairment, they make vowel errors like, substitution, neutralization, diphthongization, nasalization, as well as diphthong splitting and/or simplification, thus affecting overall speech intelligibility, and could be studied via various vowel metrices.

Speech is one such phenomenon, characterized by rapid changes in articulation which is reflected in its acoustic product. This fluidity of speech creates great challenges in its analysis. Acoustics analysis is a non-invasive method of analyzing the dynamics of speech to represent its goals, targets and/or steady state. This approach has been studied extensively especially with vowel formant measurements (F1 and F2). Interpretation of articulatory dynamics have been studied using these formants as early as 1940s by John and Delattre (1948). This is especially because formant descriptions are suited to articulatory interpretations of acoustic data and are therefore fundamental to discovery of features in articulatory-acoustic conversion. Also, F1 and F2 values have been used to construct an acoustic working space and to discover how this space relates to an articulatory working space based on kinematic data or an auditory decision space for vowel identification. As derived measures of vowel acoustics depends on formant values F1 and F2, these measures can be used to develop principles to throw light on the articulatory working space based on the acoustic working space. Vowel formant frequencies are among the most frequently reported acoustic measures of speech and are used in a variety of applications including automatic speech recognition, studies of speech production and speech perception in various populations of speakers, and clinical assessments in a range of speech, voice, and language disorders.

Abundant literature is available focusing on vowel acoustics in various languages, and a considerable difference in the vowel pattern of normal and disordered population can be observed. Various measurement techniques have been used for a number of studies since 1940s. The advancement of technology could have made differences in findings since then. It can be noted that there are: a) advances in the methods employed to study the different characteristics of speech; b) advances or innovative methods in the habilitation/ rehabilitation of children with hearing impairment; c) constantly changing advanced technology employed in hearing aids and cochlear implants giving maximum benefits in auditory perception; d) increased applications of the study with advances in technology. Also, with the technological advancement speech acoustics is getting attention among other professionals. Electronic Engineer, Acoustic Engineer, Physicist and Linguists are few professionals interested towards speech and its acoustics. These professionals might have contributed to the field of speech science in collaboration with Speech-Language Pathologists. There is lack of proper documentation of these recent advances i.e., both technologically and professionally. As cited earlier, abundant review of literature is available on derived acoustic measures of vowels in English. It is a known fact that vowels across languages subtly vary on their acoustic measures. As such compiled review literature does not exist in Asian languages, it’s all more important to explore these languages. Hence, the motivation of the present study arises from the fact to understand similar studies conducted in the Asian continent and compile them to aid in further clinical research.

Ample number of reports from countries like USA and European countries have been frequently reported and are readily available in the databases. But such studies from Asian countries are rarely reported in the global platform and are difficult to access. Vowel acoustics have been studied in multiple languages across countries in Asia. For e.g. over 20 languages are spoken in India. Multiple studies related to various vowel acoustic measures also have been carried out across languages. Though vowel acoustics have been often explored in various languages, there lacks proper documentation on these findings based on various measurement procedures. Hence, compilation of these findings in various languages across countries for children with hearing impairment, to add on evidence for both clinical utility and research purpose is warranted.

Studies on derived measures of vowel formant frequencies like Vowel Space Area (VSA), Formant Centralization Ratio (FCR), Vocalic anatomical functional ratio (F2i/ F2u ratio), Vowel Articulation Index (VAI) have shown differences between children with communication disorders, especially in children with speech motor disorders and typically developing children. Though recent studies have analyzed the derived acoustic measures of vowels like VSA, FCR, VAI, F2i/ F2u ratio in typically developing children and subjects with speech motor disorders (Vorperian et al., 2019; Fletcher et al., 2017), there is a dearth of literature exploring the same measures in children with hearing impairment. There are very limited studies which have explored the derived acoustic measures of vowels in languages across Asian countries. A vast research gap does exist and, hence need to explore the acoustic characteristics of vowels in hearing children in Asian languages is immense as there have been advancements in the wide range of health care facilities including hearing and hearing related disorders, like hearing impairment among children. The number of hearing-impaired children is being diagnosed and intervened timely due to increased newborn screening programs that are being implemented in health centers. Along with this government's policy to provide financial support for cochlear implants in countries like India and Nepal have resulted in increased number of cochlear implants. There is a need to look for changes in the acoustic characteristics and derived acoustic measures in these children across languages. As mentioned earlier, children with hearing impairment are being diagnosed and rehabilitated timely which can have impact on the acoustic characteristics of their speech, as acoustic characteristics of speech varies across ages.

Literature reports of applications of vowel-derived measures in the analysis of developing speech and/or speech of hearing-impaired children (Eliasova et al., 2013; Lin et al., 2012; Mahler & Ramig, 2012; Pettinato et al., 2016a; Roy et al., 2009; Sapir et al., 2007; Takatsu et al., 2017; Wenke et al., 2010). Studies have noted the clinical relevance of derived measures of vowel formant frequencies like Vowel Space Area (VSA), Formant Centralization Ratio (FCR), Vocalic anatomical functional ratio (F2i/ F2u ratio), Vowel Articulation Index (VAI) across various disorders of communication, including hearing impairment. Fougeron and Audibert (2011) noted that use of different acoustic metrics better accounts the differences between speakers with dysarthria and control group. Kent and Vorperian (2018) also emphasize use of combination of measures like measures of vowel space area and vowel centralization in accounting the differences in speech of clinical and control group. These measures carry clinical significance in measuring treatment outcomes and rehabilitation of children with hearing impairment. The need to compile comparable research data for further clinical application is immense Hence, there is a need for a study that compiles such findings to strengthen the measurement procedures of vowel acoustics in children with HI for choosing an evidence- based method by the clinicians.

Thus, these measures carry clinical significance in measuring treatment outcomes and rehabilitation of children with communication disorders like hearing impairment. Based on the most used and most relevant derived measure, soft wares can be developed for vowel assessment and correction. The need to produce a comparable systematic review on derived measures of vowels for further clinical application is immense. Hence, the present study is extremely warranted.

1.2 Aim of the study

To systematically review the studies on derived measures of vowel acoustics in children with hearing impairment.

1.3 Objectives of the Study

The specific objectives of the study are:

1. To compile the studies on the derived measures of vowel acoustics on children with hearing-impairment in various languages across countries in the Asian continent from multiple databases.

2. To compile derived measures of vowel acoustics based on static formant values (e.g., vowel space area).

3. To describe variations in the methodology and the procedures used in obtaining derived measures of vowel acoustics, and their findings across available literature report

1.4 Implications of the study

1. The present systematic review helped in understanding the gap in the literature in terms of derived measures of vowel acoustics in children with hearing impairment in the Asian context
2. It helped in understanding the limited research conducted in the area of vowel acoustics among children with hearing impairment and also in knowing the most often used derived vowel metric.
3. It also helped in adding information to the existing literature related to derived measures of vowel acoustics.

Chapter 2

METHODS

The aim of the study was to systematically review the studies on derived measures of vowel acoustics in children with hearing impairment.

2.1 Review Questions

The study was performed with the following questions.

1. Are there differences in the derived acoustic measures of vowels in children with hearing impairment across languages in Asia?
2. Are there differences in the procedures used to evaluate the derived measures of vowel acoustics in children with hearing impairment?
3. Are there differences in the findings of various derived measures of vowel acoustics in the vowel production of children with hearing impairment?

2.2 Searches

The review was carried out using Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. Possible key-words, related search words, their derivatives, and Medical Sub Headings (MeSH) terms relevant to the research question were developed and included:

"Vowels" OR "Vowel Space Area" OR " Vowel Dispersion" OR " Formants" OR " Formant Frequency" OR " Forman Bandwidth" OR "Acoustic Analysis" OR " Speech Acoustics" OR " Formant Centralization Ratio (FCR3)" OR "Vowel Articulation Index" OR Vocalic Anatomical Functional Ratio (VFR)" OR " Hearing Impairment" OR " Hard of Hearing” OR “Children” OR “ Child Language” OR Child Preschool” OR” Pediatrics” OR “Speech Production Measurements/Methods” OR “Speech Production Measurements/Standards” OR “ India” OR “Asia”.

These search words were used in various databases for literature search. These databases included both national databases (IndMed, J- ISHA, and institutional databases like AIISH Repository) and international databases (PubMed/Medline, Google Scholar, J-Gate, Science Direct, and Com-Disdome (ProQuest) and PsyNet. Attempts were made to include Scopus, Web of Science, Cochrane for literature search. But due to technical limitation like lack of subscription, these databases could not be accessed. Details of the kinds of literature obtained from various databases have been depicted in figure 1 in the result section.

2.3 Criteria for inclusion of Literature

Literature selection was based on the following guidelines

a) Published in peer-reviewed journals from 2015 to 2020.
b) Reports available in English
c) Participants within 15 years of age and

   diagnosed with Hearing Impairment since birth.
d) Included at least five children with hearing-impairment as participants.
e) Included instrumental analysis rather than subjective analysis.
f) Included derived measures of vowels (at least one).

2.4 Data Extraction (Selection and Coding)

The titles and/or abstract obtained through the search strategies were screened to identify the studies that meet the inclusion criteria. Those titles/or abstract with any relevant keywords or MeSH terms were passed on to further analysis and were discarded if they did not fulfill inclusion criteria. The full text of the potential studies was then retrieved and matched for eligibility.

A standardized, pre-piloted form (see Appendix 1) was developed and used to extract the data from the selected studies. Two professionals (Speech Language Pathologists) from the field of communication disorders validated the form. Necessary changes were made as per the suggestions from these professionals. The extracted information included: Study population, methodology, participant demographics and /or disorder characteristics, data relating to derived measures, including assessment procedures and the outcome of the derived measures. Also, information on year of publication, type of publication, study design, research type, the focus of research, the origin of study, and author details with their affiliation were extracted from the eligible studies meeting the inclusion criteria. Studies that reported the acoustical analysis of vowels in disorders except hearing impairment were fully discarded.

Quality assessment of the selected articles was carried out using AXIS critical appraisal for cross-sectional studies by Dr. Martin Downes (Downes, 2016) .The findings are shown in the results section in detail.

Chapter 3

RESULTS AND DISCUSSION

3.1 Records/Article Selection

A total of 1122 articles were identified using database searches, which excluded 208 duplicates. A total of 914 articles were selected for the title and abstract screening. From those, 36 articles were selected for full-text screening. Eight articles that met the inclusion criteria were selected for the study. The selection process was validated by inter-judge selection and followed by discussion. PRISMA guidelines (Selcuk, 2019) were followed for the selection of the relevant articles. The detailed PRISMA flow diagram for the selection of studies is in Figure 1.

Out of the total records / articles identified through database search (N= 1122), 765 articles were obtained from ProQuest, 300 from PubMed followed by 41 from J-Gate,13 from PsyNet and 3 from Google scholar. 208 duplicates obtained from various databases were removed using Endnote citation Manager. Title and abstract screening were carried out for 914 articles after removing duplicate articles. Out of which 878 articles were excluded as they did not either include the keywords or meet the inclusion criteria of the study. Finally, 36 articles were selected for full-text assessment. From these 36 articles, 22 were excluded due to the following reasons as in table 3.1.

Table 3.1

Reasons for exclusion of Articles

Reasons for exclusion	**No. of articles excluded**
Full-text article from outside Asia	16
Age of participants above 15 years	2
Lack of derived measures of vowel acoustics outcome	4

Finally, eight studies after assessing full texts were selected for the review.

Summary of the selected articles are presented in Table 3.3.

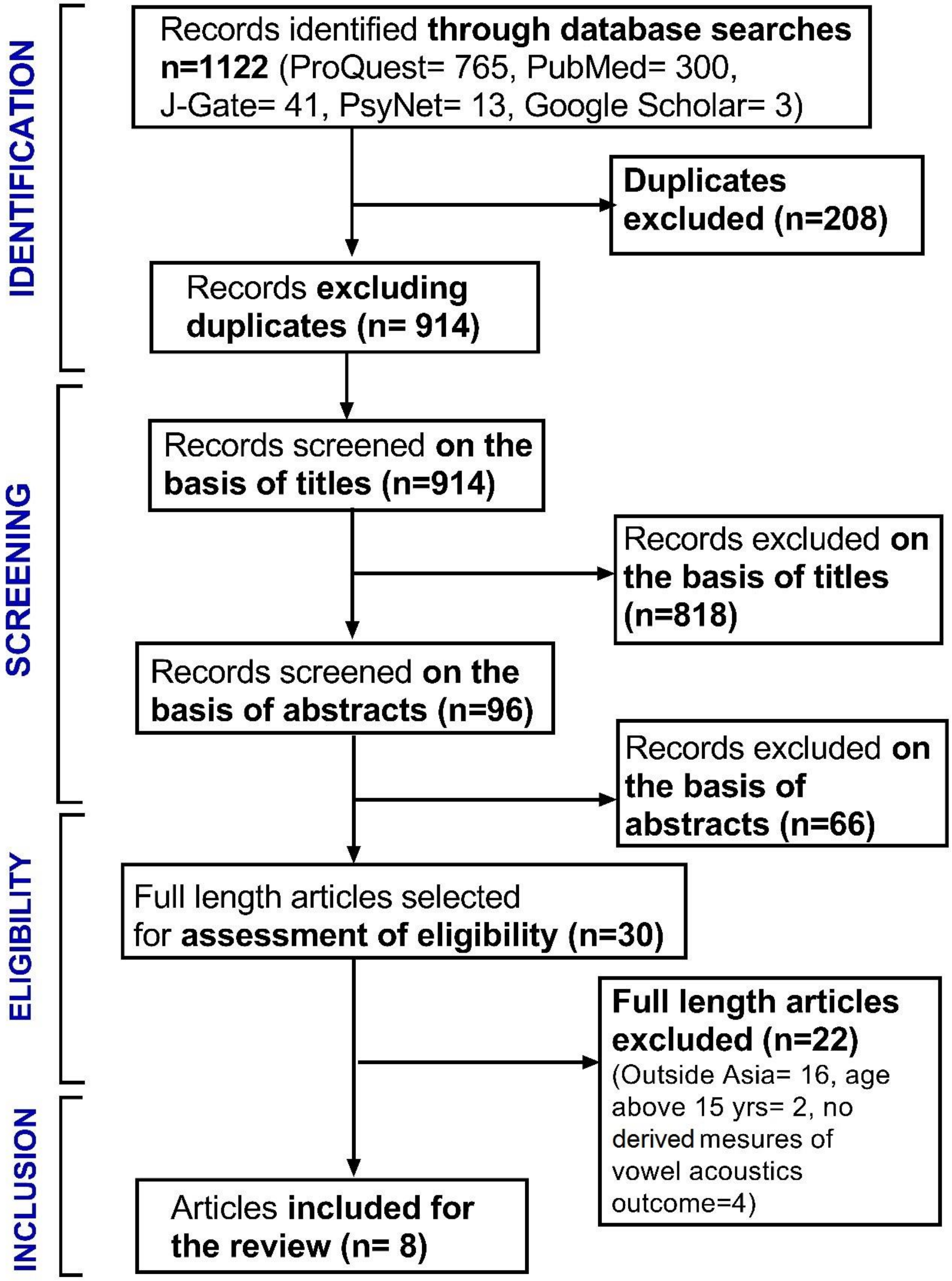

Figure 3.1 Prisma Flowchart for selection of the articles

3.2 Quality Assessment

Quality Assessment was carried out using AXIS critical appraisal (CA) developed by Dr. Martin Downes (Downes, 2016) for the systematic analysis and look into the reliability of the selected studies. It has 20 questions to analyze the article and looks into all the sections of the paper in detail to minimize the bias. The questions depicted in table 3.2 below was the order of the items presented in a cross-sectional study. The aim of the tool is to aid systematic interpretation of a cross-sectional study and to inform decisions about the quality of the study being appraised (Downes, 2016). The questions in the tool are marked as "Yes', 'No' or "Don't Know," depending on the question's requirement.

On analysis, it was found that all the studies were of good quality. There were 12 out of 20 questions answered as "Yes," which indicates good quality appraisal. Question no.19 includes a positive response with the answer "No"; hence it could also be accounted to add to the strength of the articles selected. There was no clear explanation for sample size and sampling methods present in the literature. However, in most of the studies, they have managed to take an equal number of subjects in disordered versus normal groups. Questions related to non-responders in the method section could not be answered properly as, none of the literature taken for review has mentioned participant attrition/non-responder. This also had an impact on the question related to non-responders in the result section again.

Table 3.2.

Quality Assessment for cross-sectional studies considered for the present study

S.N	Question	Abraham, 2019	Jafari et al., 2016	Yang & Xu, 2017	Hung et al., 2017	Susan Reni et al., 2020	Naderifar et al., 2019	Joy & Sreedevi, 2019.	Yang et al., 2015
	Introduction								
1	Were the aims/objectives of the study clear?	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
	Methods								
2	Was the study design appropriate for the stated aim(s)?	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
3	Was the sample size justified?	🟨	🟥	🟥	🟥	🟥	🟥	🟥	🟥
4	Was the target/reference population clearly defined? (Is it clear who the research was about?)	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
5	Was the sample frame taken from an appropriate population base so that it closely represented the	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨

	target/reference population under investigation?	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨
6	Was the selection process likely to select subjects/participants that were representative of the target/reference population under investigation?	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
7	Were measures undertaken to address and categorize non-responders?	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
8	Were the risk factor and outcome variables measured appropriate to the aims of the study?	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
9	Were the risk factor and outcome variables measured correctly using instruments/measurements that had been trialled, piloted, or published previously?	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
10	Is it clear what was used to determining statistical significance and/or precision estimates? (e.g., p-values, confidence intervals)	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩

11	Were the methods (including statistical methods) sufficiently described to enable them to be repeated?	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
	Results								
12	Were the basic data adequately described?	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
13	Does the response rate raise concerns about non-response bias?	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
14	If appropriate, was information about non-responders described?	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨
15	Were the results internally consistent?	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
16	Were the results presented for all the analyses described in the methods?	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
	Discussion								
17	Were the authors' discussions and conclusions justified by the results?	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
18	Were the limitations of the study	🟩	🟩	🟥	🟩	🟥	🟥	🟥	🟩

	discussed?	🟩	🟩	🟥	🟩	🟥	🟥	🟥	🟩
	Other								
19	Were there any funding sources or conflicts of interest that may affect the authors’ interpretation of the results?	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
20	Was ethical approval or consent of participants attained?	🟩	🟩	🟨	🟨	🟩	🟨	🟩	🟨

Yes 🟩 Don’t Know 🟨 No 🟥

Table 3.3.

Summary of the selected studies

Author/Year	**Country of origin and Language**	**Participants Demographics**	**Derived Measures assessed**	**Formula Used**	**Outcome of Derived Measures**
Abraham et al., 2019	India, Hindi	Total Participants- 46; Typically Developing (group I) -30 Hearing Impaired (group II) -16 Age range-3 to 9 years	1. FCR3 2. VSA 3. VAI4 4. VFR	$VSA = 0.5 \times [(F2i \times F1ae + F2ae \times F1a + F2a \times F1u + F2u \times F1i) - (F1i \times F2ae + F1ae \times F2a + F1a \times F2u + F1u \times F2i)]$ $FCR3 = \frac{(F2u + F2a + F1i + F1u)}{(F2i + F1a)}$ $VAI4 = \frac{(F2i + F2ae + F1ae + F1a)}{(F1i + F1u + F2u + F2a)}$ $VFR = \frac{F2i}{F2u}$	1. VFR, VAI4, and VSA -Higher in group II than group I 2. FCR3 higher in group I than group II

Jafari et al., 2016	Iran, Persian	Total Participants-40; Typically Developing (group I) - 20 Hearing Impaired (group II) -20 Age range-5 to 9 years	VSA	$\mathrm{Area} = 0.5\times\{(/i/F_2\times/æ/F_1 + /æ/F_2\times/a/F_1 + /a/F_2\times/u/F_1 + /u/F_2\times/i/F_1) - (/i/F_1\times/æ/F_2 + /æ/F_1\times/a/F_2 + /a/F_1\times/u/F_2 + /u/F_1\times/i/F_2)\}$	VSA smaller for group II than group I
Yang & Xu, 2017	China, Mandarin	Total Participants-28; Typically Developing (group I) – 14; Age range- 3 to 9 years Hearing Impaired (group II) -14; Age range-2.9	ED	$VSL_n = \sqrt{(F1n+1-F1n)^2 + (F2n+1-F2n)^2}.$	ED shorter in group II than group I.

		to 8.3 years			
Hung et al., 2017	Taiwan, Mandarin	Total Participants-54; Typically Developing (group I) – 26. Hearing Impaired (group II) -28; Sub-Group-I(CHL)-11 Sub-Group-II (MHL)-10 Sub-Group-III (SNHL)-7	VSA ED	$\frac{[F1i \times \lvert F2a - F2u\rvert + F1a \times \lvert F2u - F2i\rvert + F1u \times \lvert F2i - F2a\rvert + F1u \times \lvert F2i - F2a\rvert]}{2}$ $\sqrt{(F1_{HSLP} - F1\overline{M}_{NH})^2 + (F2_{HSLP} - F2\overline{M}_{NH})^2}$	1. VSA smaller in group II than group I (CHL and MHL smaller than SNHL and typically developing) 2. ED greater for sub-group I than other all groups (group I, sub-group II and III)
Reni et al., 2020	India, Tamil	Total Participants-30; Typically Developing	VSA	VSA= ABS {[F1i * (F2a- F2u) + F1a * (F2u - F2i) + F1u* (F2i -F2a)]/2}	VSA smaller in group II than group I

		(group I) – 20; Age range- 3 to 7 years Hearing Impaired (group II) -10; Age range-3 to 7 years			
Naderifar et al., 2019	Iran, Persian	Total Participants- 80; Typically Developing (group I) – 40; Age range- 7 to 9 years Hearing Impaired (group II) -40; Age range-7 to 9 years	FCR VSA F2 ratio	$\text{FCR} = (F2u + F2a + F1i + F1u)/ (F2i + F1a)$ $\text{VSA} = \text{ABS} ((F1i * (F2a - F2u) + F1a * (F2u - F2i) + F1u * (F2i - F2a))/2)$.	1. VSA and F2 ratio smaller for group II than group I 2. FCR larger for group II than group I

Joy & Sreedevi, 2019.	India, Malayalam	Total Participants- 30; Typically Developing (group I) – 15; Age range- 4 to 8 years Hearing Impaired (group II) -15; Age range-4 to 8 years	VSA	MATLAB (7.9.0.529) based program (developed by Department of Electronics, AIISH, Mysore, 2015) to obtain the vowel triangle and vowel space area.	No difference between the two groups
Yang et al., 2015	China Mandarin	Total Participants- 74; Typically Developing (group I) – 60; Age range- 3 to 9 years Hearing	ED VSA	$AD_{jk} = \sqrt{(F1_{jk} - F1'_{j})^2 + (F2_{jk} - F2'_{j})^2},$	Longer acoustic distance in group II than group I Variability among the VSA findings (minimal to maximal variations)

		Impaired (group II) -14; Age range-2.9 to 8.3 years			I group II compared to group I

Note: FCR- Formant Centralization Ratio, VSA- Vowel Space Area, VAI4-Vowel Articulation Index, VFR-Vocalic Anatomical Functional Ratio, AD/ED-Acoustic Distance/Euclidean Distance

3.3 Objective 1: Compilation of the studies on derived measures of vowel acoustics in children with hearing impairment in various language across Asia available from various databases.

3.3.1 Number and availability of reports in different databases

The results of a web search on the most popular database identified only eight articles reported from Asia that specifically studied various measures of vowels acoustic from 2015 to 2020, depicted in table 3.4

Table: 3.4.

Different databases and number of reports obtained from them.

Databases	Number of Records Identified, n=8(%)
PubMed/MedLine	3 (37.5%)
Google Scholar	2 (25%)
ProQuest	1 (12.5%)
J-Gate	1 (12.5%)
Google Search	1 (12.5%)
Total	8 (100%)

Hence, hidden data (not available online) are a significant drawback in vowel acoustics research scenarios as in-house publications remain unknown and inaccessible for other researchers globally. The researchers who are aware of the possible institutes and organizations involved in vowel acoustics research may specifically search for information but many, including current investigator, might miss out on relevant research reports unless it gets published on a widely accessible source. Also, there exists a large number of databases for scientific literature. However, many of them require a subscription that is paid. This makes the researcher/investigator in the particular field to hold back from his/her research interest.

The field of acoustics has grown to its fullest globally since its first use in the 1940s during the second world war. However, though it is surprising that research carried out in this domain is fundamental in nature, very few studies are being reported in Asian countries. The probability is that this kind of study is less interesting to most of the new investigators or professionals involved in the field of speech science. This might have resulted in very little reported data or literature in the open databases for those interested. For this, those interested in speech acoustics should take the lead and attempt to compile those studies through various sources. Most of the unavailable sources openly and easily not accessible are literature published within a house (Institutional databases) or in local journals that are not indexed. Hence, the researcher also should attempt to develop a good study design/methodology that could have a good impact on the indexed international journals like JSHLR (Journal of Speech-Language and Hearing Research) or ASHA wire.

Another major contributing factor is the limited number of studies found is those that are unpublished or data that is made available to a minimal number of researchers. This can again limit the progress in vowel acoustic research globally. If the research is published, this can help make the research report known for its areas under study, novel methodology and institutions with technologies available, and the researcher carrying out the study. This can increase awareness among and within the professionals (Acoustic Engineers, Speech-Language Pathologists, Software developers, etc.), which can increase collaboration between these professionals. These collaborations can help in the development of newer technologies for the management of communication disorders. So, minimize the wastage of resources and improve performance in work by sidestepping duplications of already conducted research work, openness to the research on acoustics of vowels is needed.

3.3.2 Professionals involved

Table 3.5 shows the various professionals involved for research in the field of vowel acoustics. Professionals from the speech and hearing field have been identified as the ones involved in developing evidence for vowel acoustics. Also, one professional each involved was from electronics, medical physics, and linguistics in collaboration with a speech-language pathologist.

Table 3.5.

Professionals involved in vowel acoustics research in the reviewed studies

Professionals Involved	**Number of Records Identified, n = 8**
Only Speech-Language Pathologists	6 (75%)
Speech-Language Pathologists and Electronic Engineer	1 (12.5%)
Speech-Language Pathologist, Medical Physicist and Linguist	1 (12.5%)
Total	**8 (100%)**

It is clear from the findings that Speech-Language Pathologists (SLPs) are mostly involved in the study. Although few other professionals have also contributed for two of the studies, they have been closely associated with an SLP. Therefore, we can assume that other professionals like acoustic engineers not being involved is due to the scope of vowel acoustics not being well understood in Asian countries. This is solely due to a lack of awareness about the scope and application of vowel acoustics by these professionals. Also, due to the lack of collaboration among professionals for utilizing the scope of vowel acoustics in both assessment and management of communication disorders, fewer professionals are involved in research from other fields.

3.3.3 Geographical Location (Country of Study)

Table 3.6 summarizes the country of origin or country where the study was done. On database search, eight works of literature fulfilled the inclusion criteria. Out of eight articles retrieved, studies on the Indian language from India were the most documented. Three pieces of literature were from India. Similarly, two studies each from China and Iran were available. Only one study from Taiwan fulfilled the inclusion criteria of the present study.

Table 3.6.

Country of Study

Country of Study	Number of Records Identified, n=8(%)
India	3 (37.5%)
China	2 (25%)
Iran	2 (25%)
Taiwan	1 (12.5%)
Total	**8 (100%)**

The literature search was carried out throughout Asian languages. Despite Asia being the largest continent globally and consisting of 48 countries, the table above reveals literature from only four countries. This suggests that the field of speech and hearing is still not well established across Asia, with fewer professionals working in the field of speech and hearing within Asia. Moreover, most countries in Asia have to explore the vast scope and practice of the field. This suggests that there have to be strong steps to create chances for professionals to explore and increase the investigations in this area of speech sciences. There exist limited institutes that produce professionals in the field of speech and hearing. Those qualified as professionals from speech and hearing too majorly focus on language disorders, and very few are into speech sciences. Another major reason for limited studies is that in most countries, even with the professional courses running, there is a lack of adequate resource persons/experts in the area of speech sciences. Nevertheless, there have been attempts from SLPs to explore vowel acoustics and attempts to apply it clinically.

3.4 Objective 2: Compilation of derived measures of vowel acoustics based on static formant values

3.4.1 Characteristics Studied

Articles selected for review were closely analyzed to look into the types of basic or applied research summary of the findings in the table below. Four out of eight studies were basic research and the remaining four were applied research. All the eight studies had standard group comparison as research design, where typically developing children were used as controls to compare. There were six different types of derived measures studied as depicted in table 3.7.

Table 3.7.

Characteristics Studied

Characteristics studied		**Number of Records Identified, n=8 (%)**
Types of research	Basic Research	7 (87.5%)
	Applied Research	1 (12.5%)
	Total	**8 (100%)**
Research Design	Standard Group Comparison	8 (100%)
	Total	**8 (100%)**
Focus of research	Exploring the Acoustic Characteristics in Hearing Impaired	8 (100%)
	Total	**8 (100%)**
Derived Measures Studied	Only Vowel Space Area (VSA)	3 (37.5%)
	Both Vowel Space Area (VSA) and Euclidean Distance (ED)	2 (25%)
	Only Euclidean Distance (ED)	1 (12.5%)
	Vowel Space Area (VSA), Formant centralization ratio (FCR) and F2 ratio	1 (12.5%)
	All Vowel Space Area (VSA), Formant Centralization Ratio (FCR), Vowel Articulation Index (VAI4), and Vocalic Anatomical Functional Ratio (VFR)	1 (12.5%)
	Total	**8(100%)**

3.4.2 Various derived measures based on formant values

Based on formants values F1 and F2 there were six different derived measures of vowel acoustics studied in eight selected articles. These included Vowel Space Area (VSA), Euclidean Distance (ED), F2 ratio, Formant Centralization Ratio (FCR), Vowel Articulation Index (VAI4), and Vocalic Anatomical Functional Ratio (VFR). Authors and numbers of articles studying these various types of derived measures are listed below in the table 3.8.

Table 3.8.

Summary of derived measures studied.

Derived Measures	Authors	Number of records/articles
Vowel Space Area (VSA)	Joy & Sreedevi, 2019	7
	Susan Reni et al., 2020	
	Jafari et al., 2016	
	Hung et al., 2017	
	Yang et al., 2015	
	Abraham et al., 2019	
	Naderifar et al., 2019	
Euclidean Distance	Hung et al., 2017	3
	Yang et al., 2015	
	Yang & Xu, 2017	
F2 Ratio	Naderifar et al., 2019	1
Formant Centralization Ratio	Naderifar et al., 2019	2
	Abraham et al., 2019	
Vowel Articulation Index (VAI4),	Abraham et al., 2019	1
Vocalic Anatomical Functional Ratio (VFR)	Abraham et al., 2019	1

3.5 Objective 3: Compilation of methodology, the procedure used to obtain derived measures of vowel acoustics and their findings in children with hearing impairment.

3.5.1 Vowel Space Area (VSA)

Vowel Space Area (VSA), a potential space obtained between F1-F2 plots of three corner vowels (/a/, /i/ and /u/), was the most studied derived measure of vowel acoustic out of all (six) measures identified from the literature. The publication details have been summarized in the table 3.9.

Table 3.9.

Summary of studies related to Vowel Space Area

Authors	**Year of Publication**	**Country of study**	**Journal**	**Name of the Article**
Preethy Susan Reni, S. Powlin Arockia Catherine, & A. Abinaya,	2020	India	Language in India	Vowel Space Area in Children Using Cochlear Implant
Deepthy Ann Joy & N.Sreedevi	2019	India	International Journal of Mind, Brain and Cognition.	Vowel Production in Malayalam Speaking Pediatric Cochlear Implant Users
Narges Jafari, Michael Drinnan, Reyhane Mohamadi, Fariba Yadegari, Mandana Nourbakhsh, & Farhad Torabinezhad	2015	Iran	Journal of Voice	A Comparison of Persian Vowel Production in Hearing-Impaired Children Using a Cochlear Implant and Normal-Hearing Children

Reni et al., 2020 investigated vowel space area (VSA) in Indian cochlear implanted children. They considered 20 Tamil-speaking children in the age range of 3 years to 7 years for the study. Total number of children were divided into two groups of 10 children each. Group 1 consisted of 10 children with cochlear implants (CI) and Group II typically developing age-matched peers (TD). Picture card of familiar word (were /k ∧ n/ (eye), /k i ɭ I/ (parrot)and /m ʊ d I/ (hair)) with vowels /a/. /i/ and /u/ in word medial position were used. Samples for children’s productions were recorded using Computerized Speech Lab 4500 with the help of Zebronic microphone. From spectrographic analysis of the word, first formant (F1) and second formant (F2) for vowels /a/, /i/, and /u/ were extracted. These extracted formants were plotted into F1-F2 plane to obtain vowel space area (VSA). Vowel space area (VSA) was then calculated from frequencies of F1 and F2 of vowels using the following formula:

$$\text{Vowel space area} = \text{ABS}\ \{[F1i * (F2a - F2u) + F1a * (F2u - F2i) + F1u * (F2i - F2a)]/2\}$$

Where “ABS” is absolute value.

Results revealed that the mean values of F1 for vowel /a/ in children using CI were lower than the typically developing age-matched peers and the mean of F2 was higher in children with CI. In addition, the mean values of F1 and F2 for vowel /i/ and /u/ were significantly higher in children using CI than the typically developing age-matched peers. Finally, the authors calculated the vowel space for two age groups. They found that VSA for the cochlear implant group was smaller (shown in the table 3.10) than the typically developing age group. They assumed that it was due to poor articulatory control for vowel production and delayed articulatory distinction for vowels due to poor hearing sensitivity and perceptual ability. Therefore, the authors recommended focusing on articulation therapy and language and listening training during intervention for CI children.

Table 3.10

VSA for CI and TD children

Group	**Vowel Space area (Hz^2)**
CI	8221.67
TD	171844.02

Similar results were obtained by Jafari et al., 2016 in Iran. They compared speech sounds produced by 20 Normal hearing children and 20 cochlear implanted children in the age range of 5 years to 9 years. Children were asked to produce six Persian vowels /i/, /e/, /æ/, /u/, /o/, and /^a/ with habitual vocal pitch and loudness and constant quality following the model provided by the investigator. All the productions were recorded in AKG Perception 220 Studio Condenser Microphone (AKG Acoustics GmbH, Vienna, Austria). On analysis by PRAAT (Version 5.1.44), formants F1 and F2 were extracted for all vowels. These extracted formants were plotted in F1-F2 plane to compute F1-F2 planar area for irregular quadrilateral using the following formula.

$$\begin{aligned}\text{Area} = 0.5\times\{(&/i/F_2\times/æ/F_1 + /æ/F_2\times/a/F_1 \\ &+ /a/F_2\times/u/F_1 + /u/F_2\times/i/F_1) - (/i/F_1\times/æ/F_2 \\ &+ /æ/F_1\times/a/F_2 + /a/F_1\times/u/F_2 + /u/F_1\times/i/F_2)\}\end{aligned}$$

where Fn is the formant number for the vowel symbol shown in the slashes; for example, /i/ F2 is the second formant for vowel /i/ (Kent & Kim,2008).

Results of the study showed F1 for vowels /i/ and /a/, also F2 for vowels /o/ and /a/ were higher in CI children than in normal hearing children, compared to other vowels. The planar area of CI children was found to be smaller as compared to Normal hearing children. The areas as calculated by the authors are shown in table 3.11. The authors believed vowel centralization was the result of limited auditory and visual feedback for vowel production. Hence, they have highlighted the importance of speech and language therapy post-surgery for near-normal production of Persian vowels.

Table 3.11.

VSA for CI and NH children

Group	**Vowel Space area (Hz^2)**
CI	77.447
NH	187.365

Contradicting the studies cited earlier, Joy and Sreedevi (2019) reported no significant difference in vowel space area of CI children as compared to typical children. They compared the production of bisyllabic (CVCV) Malayalam wordlist containing vowels /a/, /i/, and /u/ by 15 cochlear implanted children with 15 typically developing age-matched groups in the age range of 4 years to 8 years. Wordlist produced by children was recorded by Olympus multi-track linear PCM recorder (Model No: LS 100) following the Picture stimuli shown in the laptop. F1 and F2 were obtained from the midpoint of the word using PRAAT software. Vowel Space Area (VSA) and Vowel triangle were obtained using values of formant frequencies that were entered in a MATLAB (7.9.0.529) based program (developed by Department of Electronics, AIISH, Mysore, 2015). Results suggested no significant difference in formant values obtained for all three vowels except F2 of vowel/u/, which was slightly higher in CI children than normal children. Similarly, no significant difference was noticed in the vowel space area for both groups. However, a slight increase in the area of the vowel in CI children was observed. The authors assumed this slight increase in the area of vowel to be due to exaggerated articulatory movements modeled during speech and language therapy. This finding is consistent with the results reported by Baudonck et al., (2011).

These findings are consistent with various previous studies (Lachs et al., 2001; Liker et al., 2007; Lindblom & Sundberg, 1970; Neumeyer et al., 2010a). They have reported that the main reason for the slightly reduced vowel space area is CI children's visual cues. The visibility of jaw height change and association of jaw position and F1 (Lindblom & Sundberg, 1970) could have made little difference in the vowel space area of CI group as compared to the normal group. In contrast, F2 is compressed due to the inability to see speakers back of the tongue by CI group resulting in restricted vowel space (Neumeyer et al., 2010a). Although these studies reported visual feedback and its role in changes in F1 and F2 values that might contribute to the difference in the vowel space, they do not report the importance of hearing(audition). CI children are majorly deprived of hearing sensitivity, resulting in an inability to differentiate and use the spectral and temporal cues for the perception of vowels that is directly reflected on the articulation of vowels (Horga & Liker, 2006; Svirsky & Tobey, 1991; Vick et al., 2001).

3.5.2 Vowel Space Area (VSA) and Euclidean Distance (ED)

Vowel Space area and Euclidean Distance (the method of quantifying vowel space expansion between a vowel and the center of the vowel space) were studied together in two of the literature. The details of the literature are shown in table 3.12.

Table 3.12

Summary of studies related to Vowel Space Area and Euclidean Distance

Authors	**Year of Publication**	**Country of study**	**Journal**	**Name of the Article**
Yu-Chen Hung, Ya-Jung Lee, Li-Chiun Tsai	2017	Taiwan	Plos One	Vowel production of Mandarin-speaking hearing aid users with different types of hearing loss
Jing Yang, Emily Brown, Robert A. Fox, Li Xu,	2015	China	Journal of the Acoustical Society of America	Acoustic properties of vowel production in pre-lingually deafened Mandarin-speaking children with cochlear implants

A cross-sectional study by Hung et. al. in 2017 studied two measures of vowel acoustics that is Vowel Space Area and Euclidean Distance.28 hearing impaired subjects were taken and were divided into three different groups i.e., conductive, mixed and sensorineural hearing loss with 11, 10 and 7 participants in each group. Similarly, 26 normal hearing subjects were recruited for the study. They recorded speech samples using phonetic chart that comprised three corner vowels /a/,/i/ and /u/ along with 34 phonetic fillers in PRAAT (Version 6.0.19). Formants F1 and F2 were extracted from the sample and used to obtain vowel space area and Euclidean distance using the following formula

a) Vowel space area:

$$\frac{[\mathrm{F1i} \times |\mathrm{F2a} - \mathrm{F2u}| + \mathrm{F1a} \times |\mathrm{F2u} - \mathrm{F2i}| + \mathrm{F1u} \times |\mathrm{F2i} - \mathrm{F2a}| + \mathrm{F1u} \times |\mathrm{F2i} - \mathrm{F2a}|]}{2}$$

b) Euclidean distance

$$\sqrt{(\mathrm{F1}_{\mathrm{HSLP}} - \mathrm{F1}\overline{M}_{\mathrm{NH}})^2 + (\mathrm{F2}_{\mathrm{HSLP}} - \mathrm{F2}\overline{M}_{\mathrm{NH}})^2}$$

Results showed that vowel /i/ was affected most despite hearing loss resulting in a smaller vowel space area compared to normal, as shown in table 3.13. Conductive loss and Mixed loss group had significantly smaller VSA than sensorineural hearing loss group as compared to normal hearing group. Euclidean distance was greater for conductive hearing loss subjects due to larger variability in formant values of vowel /i/. However, other two groups of hearing loss had no such significant difference as compared to normal.

The findings of the conductive group to be smaller VSA were reported to be due to age difference, as the chronological age of the conductive group was around nine years compared to the other two who had mean age around 14 years. However, in contradiction

VSA has been found to be smaller with increase in age (Flipsen & Lee, 2012a; Pettinato et al., 2016b; Vorperian & Kent, 2007b). Also, in contrast, reduced VSA is supported by the fact that conductive hearing loss individuals depend on bone conduction pathway rather than air conduction pathway. Bone conduction helps in transduction of low frequency sounds better than high frequency (Hedrick, 2012). As vowel /a/ and /u/ has formants falling into low to mid-frequency region, the conductive hearing loss group easily perceives them as compared to /i/ with F1 in the low- frequency region while F2 falls in the high-frequency region (Hung et al., 2016).

Table 3.13.

Vowel Space Area in Hearing Impaired and Normal Hearing Group

Group	**Vowel Space area (Hz^2)**
Normal	1168989
Sensorineural Hearing Loss	811756
Mixed Hearing Loss	681646
Conductive Hearing loss	584634

Yang et. al., (2015) analyzed acoustic properties of vowels in Mandarin-speaking pre-lingually deafened children. They took 14 pre-lingually deaf children from age range 2.9 to 8.3 years. Also, 60 normal-hearing children in the age range 3.1 to 9.0 years were recruited. They were asked to produce 23 mandarin monosyllables containing seven Mandarin vowels [i, ɿ, ʅ, a, u, y, ɤ] following a model by experimenter. A total of 47 tokens in the word list for the CI children and 44 tokens in the word list for the NH children were used. All speech samples were recorded through an Electro Voice (Grasbrunn, Germany) omnidirectional microphone (Model RE50B) to a Sony (Tokyo, Japan) portable DAT recorder (Model TCD-D100) with a 44.1kHz sampling rate. Speech program TF32 was used to extract formants F1 and F2. Obtained formants were normalized using The Lobanov normalization process (Lobanov, 1971) that converted all the values into z-score. These z-scores were further normalized using the formula proposed by Thomas and Kendall (2007):

$$F'_1 = 250 + 500(F^N_1 - F^N_{1MIN})/(F^N_{1MAX} - F^N_{1MIN}),$$
$$F'_2 = 850 + 1400(F^N_2 - F^N_{2MIN})/(F^N_{2MAX} - F^N_{2MIN}),$$

F0i is a rescaled normalized formant; F^N i is a Lobanov normalized formant value for an individual speaker; F^N_{iMIN} and F^N_{iMAX} are the minimum and maximum values Lobanov normalized F^N across the entire dataset. These normalized formants were used to calculate acoustic distance /Euclidean Distance (ED) using the following formula:

$$AD_{jk} = \sqrt{(F1_{jk} - F1'_{j})^2 + (F2_{jk} - F2'_{j})^2},$$

where F10j is the group means of F1 for all NH children for vowel j and F1jk is the mean F1 of vowel j for the kth subject. F20j is the group mean of F2 for all NH children for vowel j, and F2jk is the mean F2 of vowel j for the kth subject.

Finally, they calculated vowel space area using formants of three corner vowels /a/ /i/ and /u/ to analyses the ED. Results revealed that most CI children’s (10 out 14) had varied vowel space areas with minimal to maximum variation compared to normal hearing children, suggesting variability in the acoustic length.

Vowel ellipses were scattered, acoustic distance and vowel duration were longer in CI/hearing-impaired children as compared to normal children. Authors assumed that the vowel production, especially /i/ in hearing-impaired children, is less consistent than normal due to less visibility of the tongue movement for correct articulation.

3.5.3 Euclidean Distance (ED)

This measure is also reported to be acoustic distance by authors. It was the second most studied measure in vowel acoustics. The details of publications related to ED are summarized in the table 3.14.

Table 3.14.

Summary of Euclidean Distance Study.

Authors	**Year of Publication**	**Country of study**	**Journal**	**Name of the Article**
Jing Yang, Li Xu	2017	China	International Journal of Pediatric Otorhinolaryngology	Mandarin compound vowels produced by pre-lingually deafened children with cochlear implants

Published in 2017 in the international journal of pediatric otorhinolaryngology, Yang and Xu in their study reported the findings on Euclidean Distance (Yang & Xu, 2017). 28 mandarin speaking children were recruited for the study which was divided into two groups, each group consisting of 14 normal hearing and 14 cochlear implanted children in the age range of 3 to 9 years. All the children were asked to repeat a list of nine Mandarin monosyllables (“ai, bao, pao, duo, tuo, jie, qie, yao, you” in Pinyin) containing four diphthongs (/aɪ/, /aʊ/, /uo/, and /i 3/) and two triphthongs (/iaʊ/ and /ioʊ/) after the experimenter and was recorded using Sony portable DAT recorder (Model TCD-D100) connected to an ElectroVoice omnidirectional microphone (Model RE50B). Total of 36 tokens (9 * 4) were recorded. The diphthongs and triphthongs covered the corner vowels /a/, /i/ and /u/ for the ED measurement. Analysis was done using the spectrographic analysis program TF32. Formants were extracted from the data of diphthongs and triphthongs at nine regular intervals (10-20-30-40-50-60-70-80-90% point) of the total vowel duration. Since the age range of the participants was wider, they normalized the obtained formants with the use of Bark scale with the following formula of Trsninmüllor (1990).

Zi = 26:81/ (1 + 1960/Fi) – 0.53

Where Fi is the formant frequency value of a given formant /i/ and Zi is the Bark value of formant /i/.

Trajectory length (TL) and spectral rate of change (TLroc) were then calculated based on the obtained Bark value. Trajectory length defined the sum of Euclidean distance between each two consecutive time points (10-20%, 20-30%, 30-40%, etc.), which was calculated by:

$$TL = \sum_{n=1}^{9} VSL_n.$$

Euclidean Distance was measured using

$$VSL_n = \sqrt{(F1n + 1 - F1n)^2 + (F2n + 1 - F2n)^2}.$$

Lastly, spectral rate of change (TLroc) was measured using

$TL\_roc = TL/(0.8d)$;

Results revealed that Trajectory length (TL) findings were similar in both groups. Euclidean Distance was found to be shorter than normal in Cochlear implanted. Also, individual variability among CI children was reported. The rate of change of spectrum that is changes in the formant value was found to be higher in triphthongs as compared to diphthongs for both the groups.

Restricted formants F1 and F2 have been reported by earlier studies in hearing-impaired children (Monsen, 1976). Findings from this study were consistent with previous studies. The children with CI produced clusters of vowels that suggested that they were still in earlier speech production. Also, the duration of compound vowels produced by CI children in the present study was longer, suggesting that they take longer to adjust their articulatory gestures for production. This is consistent with the studies by Monsen (1974) & Yang et al.(2015b).

3.5.4 Vowel Space Area (VSA), Formant Centralization Ratio (FCR) and F2 ratio

Single literature was found reporting findings from these three derived measures. Publication details of the study has been summarized in table 3.15.

Table 3.15

Summary of Vowel Space Area (VSA), Formant Centralization Ratio (FCR) & F2 ratio

Authors	Year of Publication	Country of study	Journal	Name of the Article
Ehsan Naderifar, Ali Ghorbani, Negin Moradi & Hossein Ansari	2019	Iran	Logopedics Phoniatrics Vocology	Use of formant centralization ratio for vowel impairment detection in normal hearing and different degrees of hearing impairment

This study intended to explore whether the use of different acoustic parameters (Formant Centralization Ratio (FCR), Vowel Space Area (VSA), F2i/F2u ratio (second formant of /i /, /u/)) was suitable or not for characterizing impairments in the articulation of vowels in the speech of HL speakers. For this, samples of 40 hearing-impaired and 40 normal children in the Persian language were taken. Three productions of each word containing three Persian vowels /a/, /i/ ad /u/ in /dVd/ context were recorded using head-mounted condenser microphone (AKG C410). The obtained samples were acoustically analyzed to extract formants F1 and F2 using PRAAT version 5.3.13. Obtained F1 and F2 were used to construct FCR, VSA, and F2i/F2u ratio using the following formula (Sapir et al., 2010)

$FCR= (F2u + F2a + F1i + F1u) / (F2i + F1a)$

$VSA = ABS ((F1i* (F2a–F2u) + F1a * (F2u–F2i) + F1u* (F2i–F2a))/2)$.

Where F1i: first formant of /i/vowel, F1u: first formant of/u/vowel, F1a: first formant of/a/vowel F2i: second formant of /i/vowel, F2u: second formant of/u/vowel, F2a: second formant of /a/ vowel.

Results showed VSA, and F2 ratio were smaller in HI group compared to normal hearing. While FCR tends to be larger in HI group and vowel centralization findings support it. Also, it was noted that with the increase in hearing severity resulted in increased centralization.

These findings suggested that FCR and F2 ratio were better in differentiating types of hearing impairment, unlike VSA. Also, FCR was better able to show the difference in the vowel articulation as compared to the other two measures. In comparison, VSA was found to be sensitive in looking inter- speaker variability. These all suggest FCR and F2 ratio to be more effective in looking for the vowel articulation in HI groups. Previous studies supported these findings, which had similar findings suggesting FCR to be good measure to assess vowel articulation. (McCaffrey & Sussman, 1994; Ozbič & Kogovšek, 2010).

3.5.5 Vowel Space Area (VSA), Formant Centralization Ratio (FCR), Vowel Articulation Index (VAI4) and Vocalic anatomical Functional Ratio (VFR)

All these metrics were studied in 2019 in the Indian population at the All India Institute of Speech and Hearing (AIISH, Mysore). The details of the study are noted in table 3.16.

Table 3.16.

Summary of Vowel Space Area (VSA), Formant centralization ratio (FCR), Vowel Articulation Index (VAI4), and vocalic anatomical, functional ratio (VFR)

Authors	Year of Publication	Country of study	Journal	Name of the Article
Ajish K Abraham, Pushpavathi M, Sreedevi N and Navya A	2020	India	International congress of phonetics	Exploring Acoustic Measures of Vowels (VSA, FCR3, VAI4, VFR) in Children with Hearing Impairment.

A cross-sectional study design was used to measure and compare formants of four vowels between hearing-impaired and normal-hearing children. 16 Hindi speaking hearing- impaired children (bilateral mixed or sensorineural hearing loss fitted with a bilateral digital hearing aid) in age range 3 to 9 years were taken. Age matched control group of 30 typically developing children (TDC) were recruited for comparison. Speech sample was obtained by asking the children to imitate the words /a:g/, /iːʃʋər/, /u:pər/, and /e:k/ embedding vowels /a/, /i/,/u/,/ae/ following an adult Hindi speaker. A precision Sound Level Meter Type B & K 2250 with sound recording software BZ 7226 was used during the recording procedure and obtained samples were analyzed in PRAAT 5.1 software to measure the formant frequencies (F1 & F2).

Obtained formant values were used to obtain five derived measures using the following formula (Vorperian & Kent, 2014).

$$VSA = 0.5 \times [(F2i \times F1ae + F2ae \times F1a + F2a \times F1u + F2u \times F1i) - (F1i \times F2ae + F1ae \times F2a + F1a \times F2u + F1u \times F2i)]$$

$$FCR3 = \frac{(F2u\ +\ F2a\ +\ F1i\ +\ F1u)}{(F2i\ +\ F1a)}$$

$$VAI4 = \frac{(F2i\ +\ F2ae\ +\ F1ae\ +\ F1a)}{(F1i\ +\ F1u\ +\ F2u\ +\ F2a)}$$

$$VFR = \frac{F2i}{F2u}$$

On analysis, formant values for four vowels were compared to other vowels. It was found that vowel /a/ had a higher formant value than other vowels in both groups. Vowel /i/ had the lowest F1 value among all vowels in TDC. While formant F1 for both /i/ and /u/ were higher in HI group and F2 lower for /i/ and /ae/. These differences in formant values had a similar impact on derived measures under study. Values for each metric are depicted in table 3.17 for both groups.

Table 3.17.

Findings for each derived measures in HI and TDC

Group	**VFR**	**VAI4**	**FCR3**	**VSA (Khz^2)**
HI	2.02	1.67	1.13	-1638
TDC	1.47	1.34	1.43	-2430

Data from table 3.17 clearly shows significant group differences. Among all the four measures of vowel acoustics, VSA was most significant in differentiating the two groups, followed by VAI4, FCR3, and VFR. Findings in this study also supported the findings from earlier studies explained under VSA, ED, and other derived measures where HI children exhibit high-frequency loss, directly depicted in vowel formants. This results in deviation in the derived measures findings as compared to typically developing children.

The present study was carried out with the aim to systematically review the derived measures of vowel acoustics in children with hearing impairment from 2015 to 2020 across the Asian countries. National and international databases were searched using key-words like vowels, vowel acoustics, derived measures of vowels, etc. A total of 1122 articles were identified, which were screened for title and abstract, following removal of duplicates that yielded 36 articles relevant to the aim of the study. These 36 articles were downloaded, and full-text screening was done to select relevant articles according to our inclusion criteria. This yielded eight articles which were then assessed qualitatively using AXIS appraisal for cross-sectional studies (Downes, 2016). Following quality assessment, the selected studies were analyzed and their details were obtained.

There were three objectives taken for the study. The first objective of the study was to compile the various studies on derived measures of vowel acoustics in hearing impaired children in various languages across countries in Asian continent. From this review we found eight studies that met the inclusion criteria. Indian languages are mostly studied in Asia followed by Mandarin in China and Taiwan, and finally followed by Persian studied in Iran to investigate various derived measures of vowel acoustics. Additionally, professionals involved for these selected studies were also compiled. Professionals like electronic engineer, medical physicists and linguists besides speech language pathologists were involved for researches in vowel acoustics. India was the country from Asia to report the highest number of literatures in derived measures of vowel acoustics in children with hearing impairment followed by China and Iran.

The second objective of our study was to compile various derived measures of vowel acoustics based on static formant values. Our review showed that there were six different derived measures used that included vowel space area (VSA), Euclidean Distance (ED), F2 ratio, Formant Centralization Ratio (FCR), Vowel Articulation Index (VAI4), and Vocalic Anatomical Functional Ratio (VFR). These were all studied independently or in the combination of one with the other. VSA was the most studied metrics among all of these mentioned measures. The details of each measure have been explained in the earlier section.

The third objective of the study was to describe variations in the methodology and document the procedure used in obtaining derived measures of vowel acoustics and their findings in children with hearing impairment. On investigation and detailed analysis, it was clear that all the studies had used similar procedures for studying derived measures. All the studies used standard group comparison considering two groups: hearing-impaired children (with or without amplification devices) and other age-matched, typically developing groups. Speech samples were collected using word lists containing the corner vowels /a/, /i/, and /u/ in all studies and were recorded using a digital microphone. The obtained samples were acoustically analyzed using PRAAT software in six studies, while two studies from China used the TF32 program for analysis. Formants F1 and F2 were obtained from the samples and used to obtain various derived measures discussed earlier with the common formula by Sapir et al. (2010) and Vorperian & Kent (2014).

Also, the third objective of the present systematic review was to compile the findings of the derived measures of vowel production in children with HI in studies which met inclusion criteria. All the studies reported that hearing-impaired groups had significant differences in the derived measures of vowel acoustics compared to normal-hearing children. The findings of each study have been explained in detail in sections 3.4 and 3.5 with the characteristics and various derived measures studied. This can be correlated with the affected formant values for the vowels under study. A typical pattern of errors was seen in hearing-impaired children taken in all the studies. They have commonly tried to explain why formants are affected, emphasizing lack of proper visual feedback that impacts the production of vowels /u/ affecting its formants. Also, authors have assumed the importance of auditory training and feedback for accurate perception and production of vowels. This is because reduced hearing sensitivity can make one deprived of getting benefit from spectral and temporal cues in auditory signals (Horga & Liker, 2006; Svirsky & Tobey, 1991; Vick et al., 2001). However, these factors are not studied in any of the studies. Hence, it is recommended for future researchers to look into these aspects also.

All the above-mentioned findings showed differences among typically developing children and children with hearing impairment. Although most of the articles have only described the acoustic characteristics of vowels with these metrics, it is obvious that these metrics could be used clinically with various communication disorders (Kent & Vorperian, 2018.; Sapir et al., 2010) . Literature shows that vowel space area is the most studied metric among six, and its application among disordered populations has been extensively reported (Kent & Vorperian, 2018). There are numerous applications of vowel-derived measures in the analysis of developing speech and/or speech of hearing-impaired children, for which acoustic methods play an increasingly large role, particularly in the inference of articulatory behaviors from acoustic data. Applications of various measures of vowel acoustics have been discussed in the upcoming section.

3.6 Application of VSA metrics

1. It has normative values for both Children and adults hence can be used to compare between normal and delayed/or disordered (Flipsen & Lee, 2012b; Kent & Vorperian, 2018a; Kwon, 2010; Pettinato et al., 2016a; Vorperian & Kent, 2007a).
2. Reports have suggested that VSA decreases with age, hence can be used to assess whether a child is developing articulatory gesture normally or not (Pettinato et al., 2016a).
3. Clinically, it has been studied with number of communication disorders (refer Kent & Vorperian, 2018.); i) Children with neurogenic disorders; ii) Adults with acquired dysarthria; iii) Children with Down Syndrome; iv) Individuals with hearing loss; v) Individuals with glossectomy; vi) Individuals with stuttering; vii) People with oral and/or oropharyngeal cancer; viii) People with stress-related or post-traumatic stress disorder.
4. VSA has also been widely used to assess the effectiveness of voice and speech therapy (Eliasova et al., 2013; Lin et al., 2012; Mahler & Ramig, 2012; Pettinato et al., 2016a; Nelson Roy et al., 2009; Shimon Sapir et al., 2007; Takatsu et al., 2017; Wenke et al., 2010).

5. Findings from VSA has been used to correlate speech intelligibility, that is VSA with higher value indicating good intelligibility and vice-versa in normal native speakers (De Boer, 2009.; Neel, 2008; Smiljanić & Bradlow, 2009), non-native speaker (Chen et. al., , 2010) and disordered populations (De Bruijn et al., 2009; Kwon, 2010; Turner et al., 2009).

3.7 Application of FCR metrics

1. Findings from vowel centralization can be used to report the vowel normalization, and differentiate the characteristic of articulation among various speakers (Karlsson et al., 2002)**.**
2. FCR is a sensitive, valid, and reliable acoustic metric for distinguishing dysarthric from unimpaired speech and for monitoring treatment effects (Sapir et al., 2010).
3. FCR are useful in characterizing the configuration and dimensions of vowel production

There have been number of other measures (VAI4, F2 ratio, etc.) reported in the recent decade that can be very useful clinically. A combination of two or more derived measures of vowel acoustics can yield good results as reported (Abraham et. al., 2019). However, there are almost negligible shreds of evidence suggesting their use in both normal and disordered populations. This is highly recommended to look out for the effectiveness of these measure through new studies.

Results from the current systematic review revealed there exists no difference in the procedure to measure vowel metrices, and findings of derived measures of vowel acoustics in children with hearing impairment in various languages across countries in Asia. Six different types (Vowel Space Area (VSA), Euclidean Distance (ED), F2 ratio, Formant Centralization Ratio (FCR), Vowel Articulation Index (VAI4), and Vocalic Anatomical Functional Ratio (VFR) of derived measures of vowel acoustics were identified from this systematic review. Findings of the studies considered for review suggest difference in derived measures of vowel acoustics in children with hearing impairment when compared to typically developing children.

Chapter 4

SUMMARY AND CONCLUSIONS

With the aim of reviewing the studies on derived measures of vowel acoustics in children with hearing impairment, literature search was carried out in various national and international databases using keywords related to vowel acoustics in various languages across countries in the Asian continent, from the year 2015 to 2020, for five years. PRISMA guideline i.e., title screening following duplicates removal and abstract screening before full text screening, was followed to find the relevant articles as per the inclusion criteria. Eight out of 1122 literatures fulfilling inclusion criteria were selected for the review. Quality Assessment of all eight articles were carried out. Information relevant to our study were retrieved in detail from each article.

We found that most of the studies related to the metrics of vowel acoustics have been done in India followed by China and Iran in the Asian continent. All the studies compared acoustical characteristics of vowels in hearing-impaired children with age matched normal hearing group of children. Six different derived measures of vowel acoustics have been studied widely, namely Vowel Space Area (VSA), Formant Centralization Ratio (FCR), Vowel Articulation Index (VAI), Vocal Anatomic Ratio (VFR), F2 Ratio and Euclidean Distance (ED). VSA was the most studied derived metric followed by VSA and ED together. Similar procedures were used to assess various derived measures of vowel acoustics in children with hearing impairment in these eight studies i.e., standard group comparison using children with hearing impairment and age-matched normal children. Vowels /a/, /i/ and /u/ were the three common vowels considered across languages using PRAAT software, across countries for study of vowel metrices. All the studies reported affected derived measures in children with hearing impairment when compared with age-matched controls.

The present systematic review helped in understanding the gap in the literature in terms of derived measures of vowel acoustics in children with hearing impairment across countries in Asia. It also helped in understanding the most often used derived acoustic measure in children with hearing impairment.

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Appendix I: Sample Form for Data Extraction

Article No:		
Name of the Article:		
Authors:		
Year of Publication:		
Journal Published on:		
Country of origin:		
Retrieved from (Name of database)		
Methodology		
1.Types of research		
2. Study Design		
3.Type of Research		
4.Participants	a.) Total	
	b) Study Group with age range	
	c) Control Group with age range-	
5.Procedure	a) Stimuli used	
	b) Language	
	c) Instrument used	
	d) Acoustical Analysis	
	e) Derived Measures Studied	
Results		