Review Article

Speech Intelligibility Index: A Literature Review

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Highlights

- SII is one of the most useful indicators in assessing speech comprehension ability
- SII depends on hearing level, age, hearing aid use, etc.
- The score of speech intelligibility index varies in different languages

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ABSTRACT

Background and Aim: Speech is known as the most important auditory signal that humans deal with it. Noise can mask speech and prevent spoken information from reaching us. Researchers have been trying to develop indexes to assess speech intelligibility. Speech Intelligibility Index (SII) is one of these indicators and we intend to introduce its nature and applications.

Recent Findings: SII is a method that numerically demonstrates the ability to hear speech in difficult listening situations. The number 1.0 indicates that all spoken information is available, while 0.0 indicates that the person does not have access to any information. Hearing loss changes a person's scores on this index, so we need to use corrective factors to more accurately estimate speech intelligibility. In children, the SII score is different from adults. This indicator can be used in the improvement of hearing aid fitting and more accurate adjustment of cochlear implants. The frequency importance function used to calculate SII has a unique shape in each language. Therefore, SII will also differ in different languages, depending on the nature of each language.

Conclusion: SII has emerged as a practical indicator among objective assessments of speech intelligibility. Many have tried to extend and prepare it for use in different groups. Therefore, care should be taken about the use of this index in hearing-impaired people, children, with hearing aids or cochlear implant patients, etc. Evaluation of this index in other languages can help to better adjust the hearing aid based on the characteristics of each language.

Keywords: Speech intelligibility index; hearing loss; children; hearing aid; cochlear implant; language

Introduction

In everyday life, speech is not always equally comprehensible to us in all situations because there are noises that can mask part of the speech signal. As a result, not all spoken information will be available to the listener for comprehension. Researchers have tried to develop special computational methods to predict the ability to understand speech in the presence of noise [1-4]. These methods have changed over time and have taken on different names and have been used in many studies [5-14].

Speech recognition tests are often used to assess hearing loss and predict hearing aid performance. Numerous spoken materials and listening situations are used for this assessment, so there needs to be a specific way to compare predictions (e.g. based on audiometric information and test difficulty) with actual assessments of the individual. To achieve this goal, there must be a practical method that is useful for real speech, auditory thresholds in the speech frequency range, and different levels of noise [15].

In situations where the signal is presented in background noise, the Speech Intelligibility Index will be calculated based on the speech spectrum, noise spectrum, and hearing thresholds of the individual. Both the speech signal and the background noise will be filtered and converted to different frequency bands. In each frequency band, the amount of audibility is obtained using the signal to noise ratio (SNR) in that frequency band. Not all frequency bands are equally important for hearing, and they do not have the same amount of speech information. As a result, weighting will be performed for each band, known as the frequency importance function (FIF), and the degree to which each frequency band contributes to comprehensibility. This function depends on various factors such as the type of speech material (such as single words or sentences) [16]. Higher speech redundancy simply results in less information (reduced SII) required to understand the speech message. Finally, SII is obtained through these aforementioned factors [17].

To write this article, a search was conducted in database articles like Google scholar, PubMed and Science Direct over the last twenty years, with keywords of speech intelligibility, speech intelligibility index, articulation index, hearing loss, children, hearing aid, cochlear implant, and language. 39 articles that were related to this topic were used to write this paper. The results are presented in several sections in the continuation of the article.

Types of speech intelligibility assessments

Hearing aids are designed to increase speech comprehension for people with hearing loss, but it is difficult to predict how much a person will actually benefit from this aid. In addition to hearing loss, speech intelligibility is influenced by factors such as resonance, ambient noise, and nonlinear noise and distortion produced by the hearing aid itself. These factors will reduce the ability to understand speech [18]. There are generally three types of speech comprehension assessments. First, objective assessments are calculated based on the number of words and sentences that a person is able to identify. Second, subjective methods use scaling procedures and third, it involves the direct evaluation of spoken information [3]. All these methods are highly correlated with each other [19-21]. Among the various assessments available for speech intelligibility, objective methods are the most widely used because they are easier and faster to perform [22]. Therefore, in this article, we have introduced one of the most famous of these objective tools, which is SII.

Definition of speech intelligibility index

The ability to understand speech is used in different cases. SII, as one of these objective methods, correlates with the ability to understand speech in difficult listening situations [22]. SII is a numerical index that estimates the audibility at different frequencies and is calculated by estimating the audibility of an average speech signal based on the hearing threshold or background noise level (whichever is greater) [23].

Difference between speech intelligibility index and articulation index

Another indicator you may have heard of is known as Articulation Index (AI). AI is a tool used to predict the amount of speech that is audible to a patient with a specific hearing loss [24]. Both indicators have a history dating back to the mid-20th century and the work of Fletcher and Galt [3]. They wanted to find a way to estimate the effect of changing telephone circuits on speech comprehension. The AI calculation method standard proposed in 1969 was introduced in 1947 by French and Steinberg [4]. Previously, behavioral techniques were used that included listening to the voices of different speakers and many listeners performing the speech test. Being high cost and time consuming were among the disadvantages of these methods. The initial difference between AI and SII is the 1997 standard, which was designed to be more flexible in defining the main input required for calculation (i.e. speech and noise levels, hearing thresholds).

This approach also allowed them to select the evaluation point (e.g. free field or at the level of the eardrum). Other features include modifications to the upward spread of masking and high presentation levels, as well as the addition of useful information such as FIF that are used in the SII calculation [25]. SII has a high correlation with speech intelligibility [26], so it can be considered as a better and more accurate indicator than AI.

Speech intelligibility index calculation

To calculate SII in any language, you must first prepare the required speech materials, which can include words, sentences, etc. [27]. These materials are recorded in a standard acoustic environment. The obtained speech signals are subjected to various high-pass and low-pass filters that have different frequencies. This divides the speech energy into smaller frequency ranges to determine how important each range is. Then the desired noise is added to it (white noise, speech noise, etc.). Noise and speech signal intensities are adjusted to obtain different SNRs. To perform the test, the person will first be placed in an acoustic room and will have a computer. He should write down or repeat each word or sentence after hearing it. The number of correctly identified words is used to calculate the individual scores in each section (word, sentence, etc.).

Individual scores are recorded in a table based on various filters. The cross-over frequency is then calculated, which is the intersection of the detection points for the high-pass and low-pass filters. In the next step, the relative transfer function (RTF) will be obtained. The point of 100% of speech recognition is marked with the number 1 and the point of 0% of speech recognition is marked with the number 0, and in the same way other points will be converted. As a result, the importance of each frequency band is calculated using this function. An equation will be used to calculate the weight significance of each frequency band to create a frequency significance function [28].

To obtain SII, the ratio of audible speech in each frequency band is multiplied by the relative importance of that band. These values are finally added together, and the desired index is obtained. The general formula of this evaluation is as follows:

In this formula, n represents the number of frequency bands used for calculation. This evaluation is flexible and allows to determine the number of used frequency bands. Indicates the importance of that frequency band and is also known as FIF, which depends on the type of test material. The sum of the FIF values in all bands will be 1.0. Ai, which has a number between 0 and 1, indicates the ratio of speech codes that can be heard in each frequency band. It is calculated based on the level of speech relative to the noise in that frequency band.

Using the basic formula for calculating Ai, we simply subtract the noise spectrum level from the speech spectrum level (in decibels) in each band, add 15 decibels (assumed speech peak), and divide by 30. Values greater than 1 or less than 0 are set to 1 and 0, respectively. This value provides a ratio of 30 dB dynamic range of speech that is audible to the listener [25].

The calculated SII rate is also interpreted as the ratio of spoken information available to the listener. Its maximum value is 1.0, which indicates that all spoken information is available to the listener. A minimum value of 0.0 also indicates that no spoken information is available [16]. If the appropriate transfer function is used, the calculated SII scores can be converted to the desired scores. Transfer functions are available today for a variety of speech materials [29-31].

SII was developed to correlate with speech comprehensibility in various adverse listening situations. The ratio of speech to noise in each frequency band, commensurate with its importance in speech comprehension, is used to calculate this index. According to the reference, a good communication system has an SII of 0.75 and above, while a poor communication system has an SII of less than 0.45 [16].

In hearing aid processing, speech is known as a desired signal. The result of many nonlinear processes, such as compression and noise control in digital hearing aids, depends on the characteristics of the input signal. So that the replacement of the speech signal with amplitude modulation noise [32] or a synthesized approximation to speech [33] changes the gains of the time and frequency domain. Therefore, a speech signal or pseudo-speech signal that is very close to normal speech should be used for estimation in nonlinear systems.

Speech intelligibility index limitations

SII is a practical indicator, however, there are limitations to it. First, the intensity of speech and noise at the level of the eardrum is required to calculate it, while such information may not be available, and we can only use pre-recorded digital signals. Second, SII ratings were mainly for non-fluctuating noise based on the long-term mean range of speech and masker. Therefore, it cannot be used in cases of fluctuating noise (such as noise of multi-speakers). Researchers have tried to solve this problem in some way and have provided models [18, 34]. For example, by dividing speech and noise into smaller 9-26 millisecond frames, you can get instantaneous AI evaluation per frame and average AI values across all frames to obtain a single AI score. This method makes the estimates somewhat more accurate than the conventional SII model [35]. SII is a useful and practical index, but it cannot be used for all environments and types of noise. As a result, we need to have extension models to increase the accuracy of evaluation.

Speech intelligibility index extensions

Because of the limitations, SII can be extended to include situations beyond what is provided in the standard. These developed models will be valid as long as the physical and perceptual assumptions have not changed [18].

To calculate SII, the speech energy spectrum and the noise energy spectrum are averaged over the duration of the stimuli. The SII is then calculated by long-term averages. The SIIs calculated in this method are suitable for stationary noise but will not be accurate for fluctuant noise. Kate developed an adaptive noise-cancellation system that divides speech into smaller sections, calculates AI for each section, and plots AI changes as a function of time to indicate system convergence [35]. Rhebergan and Versfeld developed the SII approach for estimating fluctuant noise. They suggested that we must divide the noise speech into segments, obtain the SII of each segment separately, and then average the SII values. SII hypotheses are based on the frequency, threshold, and masking resolution in their process, but additional analysis allows us to better understand the effects of signal fluctuations and the ability to listen in noise valleys [15].

In the studies, the SII model basically considers non-oscillating noise. People with normal hearing have almost always better performance in fluctuant noises [13, 14, 36-49]. This phenomenon seems to be explained by the fact that a person in fluctuant noise can capture the speech glimpses present in the noise intervals [38, 45, 50]. The nonlinear behavior of the basilar membrane at noise intervals will increase the gain. This behavior is not the case in hearing-impaired people because they do not have such a nonlinear mechanism, or it is less so the ability to hear is reduced in the presence of a masker [51-53]. The SII in fluctuant noise will not be able to accurately predict speech comprehension. Other models do not have this capability. Rhebergena and Versfeld developed the SII model in a way that it could also be used for fluctuant noises [15].

Speech intelligibility index in normal-hearing individuals

There are several methods for estimating speech intelligibility in normal individuals. The best known of these is AI [2, 3], which was later changed by American National Standards Institute (ANSI) to SII [16] and Speech Transmission Index (STI) [32, 54]. SII refers to the calculation of the SNR at each frequency, with subsequent adjustments for the hearing threshold and masking effects in the frequency domain. Total weighted SNRs at different frequencies are used to estimate intelligibility. SII is effective for stationary additive noises and STI is effective for reverberation and can be done with speech stimuli. [55].

To predict speech perception scores by SII, a transfer function is needed that shows the relationship between SII and speech perception. The SII model is very accurate in estimating the scores of people with normal hearing [56, 57]. In deaf people, a correction factor is needed [4, 57-60]. These correction factors can increase the accuracy of the estimation in cases of mild to moderate hearing loss but will not be very accurate in cases of above moderate hearing loss [57, 60, 61]. It makes sense that this is also the case for cochlear implant users, as their hearing loss is severe to profound. On the other hand, reductions in auditory processing and wide interpersonal differences in cochlear implant users can also complicate SII estimation.

Speech intelligibility index in specific groups

Speech intelligibility index in the hearing-impaired individuals

The shape of the frequency importance function of hearing-impaired people differs from that of normal hearing. One study found that the participation of frequency bands in speech recognition was inversely proportional to the hearing threshold. This is probably due to the reduced ability to hear sounds, even if we raise the intensity to compensate.

SII in some cases overestimates speech comprehensibility for the hearing-impaired persons [61-64]. One of the suggested solutions to this problem was to add a correction factor for SII, which is proportional to the individual's hearing loss [57, 65]. This factor leads to a more accurate empirical estimate. However, it does not explain why SII and the perceptibility observed in patients, differ. The accuracy of this correction factor can be mproved by some methods [60]. The higher a person's hearing threshold, the lower the SII for the same sensation level (SL). This correction is higher for high frequencies than low frequencies and is higher at high SLs than at low SLs [60]. The second solution is to adjust the effective SNR for these people. Decreasing the SNR reduces the estimated SII. Numerous studies have performed these calculations in deaf people using different methods [4, 7, 64, 66].

Speech intelligibility index in children

SII has been extensively studied in people with hearing loss and hearing aids and is used as a method to show the relationship between speech signal and speech recognition scores. But these studies have been few in the case of normal children and children with hearing loss. One of these studies performed by Scollie on adults and children with or without hearing loss showed that the SII model could not be used to accurately estimate children's cognition, so the proficiency factor for age and hearing loss is necessary [66].

To understand speech [66] and vocabulary learning [67], children need a higher level of hearing compared to adults, i.e. they need a higher SNR and more bandwidth [5]. Higher audibility is achieved due to wider bandwidth, higher sensation level or different hearing thresholds [68-73]. Children also need a higher SNR to understand words and sentences in the presence of noise [74-77]. Therefore, to ensure that the child has access to sufficient auditory information, it is necessary to assess the ability to hear sounds to ensure the natural process of language development. Assessing speech recognition in children is a bit difficult, and clinicians use indirect methods (such as SII [16]) to estimate the ability to hear sounds. These methods are based on hearing aid output in terms of aided SII.

Speech intelligibility index importance in hearing aid users

Hearing loss is a common problem in communities that has many social and economic effects. It is estimated that about 40% of adults between the ages of 20 and 79 experience some degree of hearing loss, which is higher in the elderly [78]. Attempts are made to adjust the prescription hearing aid for patients in a way that delivers the required gains to the patient [79]. Hearing aid output can be improved using methods such as real ear measurement (REM) or coupler to be close to the expected output [79-81]. This leads to good results when prescribing to patients [82-85]. However, many fittings do not work with these methods, so the use of hearing aids is low. Studies have shown that not adjusting according to the targets and not verifying the hearing aid, are associated with low use of the hearing aid [86], poor speech recognition, reduced benefits perceived by the person [79, 85, 87-89] etc.

Gain, frequency response and compression commensurate with the patient's hearing loss, are among the goals of the prescription. The performance of the fitting can be measured by methods like the similarity of the hearing aid output to the target and the ability to hear the recorded speech signal using the aided hearing aid. These can be influenced by factors such as audiometric characteristics and factors related to the hearing aid (style of hearing aid, vent) and differ from our expected output of the prescription [90, 91].

The SII is used as one of the important criteria to determine the efficiency of hearing aid prescription [92]. Different degrees of hearing loss can affect the rate of SII [93-96]. These effects have also been studied in hearing aid children and its norm values have been reported [97].

Speech intelligibility index importance in cochlear implant users

A cochlear implant (CI) is a prosthesis that converts an acoustic signal into an electrical stimulus to eventually stimulate the auditory nerve fibers. Studies have shown that the higher the dynamics of CI (i.e. the lower the person's hearing threshold), the better his/her speech recognition performance [98, 99]. However, CI adjustment is mainly based on loudness comfort, not hearing.

Children should use hearing aids periodically before receiving CI so that if hearing aids do not work well, they will have CI surgery. The child's performance, including language development and speech comprehension, can be predicted by SII using a hearing aid. As some have reported, a hearing aid SII of less than 0.65 indicates a significant delay in the vocabulary development of these children [100]. Therefore, SII is more important than pure tone average in determining speech access and hearing aid benefit. Children with profound hearing loss are less likely to reach target gains, so they have less access to information and a lower SII. These children are within the scope of CI candidacy, and it is possible that this prosthesis could provide greater, clearer, and better access to linguistic information than hearing aids [23]. Some researchers have suggested that in addition to the existing criteria for CI candidacy based on hearing thresholds, SII should be used and children with SII less than 0.65 should also be considered as cochlear implant candidates [23].

Conventional SII in CI users cannot be a good predictor of a person's speech performance due to their very poor hearing and the many individual differences that exist between them. So, a group has tried to adapt this model by making changes. These studies include research by Lee et al. that suggests the use of demographic information (audibility with aid and duration of hearing loss) and cognitive skills (gap detection and auditory digit span results) increase SII accuracy [100].

Speech intelligibility index in different languages

Differences in phonemes, sentence structure, and the distribution of linguistically distinctive speech cause different languages to have different FIFs [101-102]. For example, in Cantonese and Mandarin Chinese, tones have a meaning and a unique linguistic nature. Changing the tone can change the meaning of a word. Because the fundamental frequencies of tones are mostly at low frequencies (between 180-1600 Hz), they play a more important role in speech intelligibility in Cantonese than in English [5]. Most of this low-frequency information is transmitted by vowels, so vowels play a more important role in speech perception in tonal languages [68, 101]. Therefore, when we want to examine the effect of hearing loss on speech comprehension in tonal languages (such as Thai or Somali), we must pay attention to the FIF of that language. Higher frequency emphasis of FIF at low frequencies means that the effect of the same hearing loss on patients with different languages is not the same. FIF has been evaluated in various languages including Malay, Korean, German, French, Swedish and Mandarin [15, 103-108].

Discussion

The studies mentioned in this paper have shown that SII has a high correlation with speech comprehensibility, so it can be considered a more accurate indicator than AI, which is used in difficult listening situations. It can be said that SII does not apply to oscillating noises and people with hearing loss, and other modified models should be used in these cases.

The actual speech comprehension of people with hearing loss is less than the SII estimation which is due to differences in the frequency importance function of these individuals. This problem can be solved by adding a correction factor or changing the SNR. Studies have shown that original SII cannot be used for children, so there is a need for a correction factor in this group in addition to the hearing impaired group. SII results can be used in hearing aid users reach more satisfaction. SII plays an important role in estimating the speech comprehension and language development of CI children and can be an effective indicator in the educational process of these children. It can also be used as an indicator in determining a child's candidacy for CI surgery.

SII assessment is necessary for any language because today's hearing aid fitting formulas are based primarily on English speech comprehension. Therefore, for better prescribing to patients, you need to know more about your language speech intelligibility index.

Conclusion

The ability to understand speech is very important in our daily lives because speech is the most important auditory signal that we deal with. Speech comprehension is measured by a variety of tools and SII is one of them. This index shows how much auditory information is available to the individual. This model has limitations that some researchers have tried to improve by making changes to the previous model. Hearing loss, age and language can affect the SII rate, so corrections are needed. This index can also be used in hearing aid and cochlear implant users and measure the person's access to auditory information to reach the best fit.

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Authors' contributions

SMRT: Study design, acquisition of data and drafting the manuscript; GM: Study design, Data analysis, interpretation, and final approval of the version to be published; HJ: Interpretation of the results and critical revision of the article.

Conflict of interest

The authors declare that they have no conflict of interest.

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