Speech Perception and Sub-Cortical Processing of Speech in Noise in Children with Dyslexia

Sudhir Kumar[1] & Dr. Prawin Kumar[2]

Abstract

Present study was carried out to investigate the sub-cortical processing of speech in quiet and in presence of noise in children with dyslexia and compared with typically developing children (N=29, age range = 8-12 years). Speech-evoked Auditory Brainstem Response (ABR) was elicited in quiet and noise with two different natural CV syllable (/da/ & /ba/) of 150 ms duration. Speech-in-noise (SPIN) performance was assessed using monosyllabic words in Indian English as behavioral measurement. Results showed that children with dyslexia had delayed latencies (poorer) of onset responses of speech-evoked ABR (wave V, wave A & slope of V/A complex) in the presence of noise for both speech syllables. Further, Mann-Whitney U test revealed statistically significant difference for wave V and wave A for quiet as well as noise condition for syllable /da/ at $p < 0.05$. However, there was no statistical significant difference found for syllable /ba/ across conditions (quiet vs noise). Sustained response includes amplitude of fundamental frequency (Fo) and harmonics (H2, H3 & H4). Result showed reduction in amplitude with increased higher harmonics. Descriptive statistics for SPIN test showed lower (poorer) mean score in children with dyslexia compared to typically developing children and Independent t-test revealed significant difference between two groups at $p < 0.05$. Spearman correlation between speech-evoked ABR and SPIN test suggested negative correlation for wave V and wave A and positive correlation with amplitude of harmonics in children with dyslexia. Present study concludes that children with dyslexia shows sub-cortical timing deficit in adverse listening condition and poor encoding ability of fundamental frequency compared to typically developing children.

Key words: *Speech ABR, Natural speech syllables, SPIN, Dyslexia*

Introduction

Developmental dyslexia is a neuro-developmental disorder in children with prevalence of 5-10% in given age group with deleterious effect on language based learning ability, educational achievement and socio-profession integration [1]. Literature reported that individual with dyslexia have poor phonological processing ability [2,3]. Despite having average nonverbal intelligence, they showed deficit with written language [4]. Children with dyslexia have impaired speech perception in the presence of background noise [5-8] exhibited greater speech perception deficit in the presence of amplitude modulated noise or for stationary noise [9]

Behavioral test in children with dyslexia showed deficit in speech perception in noise [8,10] impaired phonological awareness skills [11] and poor temporal processing [12]. It is well established that neural synchrony is degraded in noise, leading to delayed and reduced auditory evoked responses from cortical [13,14] and brainstem structures [15,16]. Electrophysiological finding showed deficits in the brainstem timing, poor temporal resolution ability and impaired representation of fundamental frequency in the presence of background noise.

There are various studies which reveal that individuals with dyslexia having difficulties in speech perception in challenging listening condition as measured by the behavioral tests [6,7]. There is also existing literature which studied the sub-cortical and cortical response using speech evoked ABR and auditory late latency response (ALLR) respectively in children with and without dyslexia [17]. These studies reported poor readers have significantly more processing difficulties based on variables in auditory brainstem response than good reader [18]. Cortical evoked potential suggested that cortical amplitudes significantly reduced in children with lower SPIN score compared to children with higher SPIN scores which reflect a developmental central processing impairment [19]. Research also reported about fundamental sensory representation of sound at brainstem and cortical levels in the learning problems children when speech sounds were presented in noise condition [15]. Since there is a limited available literature to explore the natural stop consonants perception in Indian population while measuring speech evoked ABR in presence of noise and speech in noise perception in children with dyslexia.

The present study is taken up with the aim of performing speech evoked ABR in presence and absence of noise in children with dyslexia and compared with typically developing children. The above population was also evaluated for behavioral speech in noise test. Finally, the relationship between behavioral (SPIN) and electrophysiological (speech evoked ABR) measurement in children with dyslexia and typically developing children were also tried to established.

1. sudhir.k@gmail.com
2. prawinaiims2002@gmail.com

Method and Materials

Participants

There were two groups of participants included i.e.; control (Group 1) and clinical group (Group 2) in the age range of 8-12 years. There were 13 typically developing children included for control group and 16 children with dyslexia were in clinical group. All participants were from English-medium school-going children in and around Mysore city. All the participants from control group have good scholastic performance as reported by parents or information collected from school teachers. The diagnosis of dyslexia made by experienced Speech and Language Pathologist and/or Clinical Psychologist.

All the participants had bilateral normal hearing sensitivity (? 15 dB) in the octave frequency range of 250 - 8000 Hz with normal middle ear functioning. Speech recognition threshold were within ± 12 dB with pure tone average threshold correlation and speech identification score were ? 90% in quiet. Transient evoked otoacoustic emission testing revealed normal functioning of outer hair cells. The click evoked ABR revealed normal neural integrity in all participants. All participants were screened using screening checklist of auditory processing (SCAP) to rule out central auditory processing disorder in both the groups. Written/oral informed consent was obtained from all the participants. All behavioral and electrophysiological tests were performed in sound treated room with the permissible noise level in room [20]. It was insured that testing rooms are well illuminated.

Behavioral Measure (SPIN)

To assess speech perception ability in presence of noise, monosyllable words [21] were presented at 40 dBSL with monaurally at 0 dB SNR.

Electrophysiological Measure (Speech evoked ABR)

Natural speech syllables /da/ and /ba/ with 150 ms duration were used to elicit speech evoked ABR. These two different syllables were chosen because they are predominantly differing in terms of acoustic features (high versus low frequency sound). Natural speech syllable voiced /da/ with duration of 150ms having fundamental frequency of 122 Hz and other formants frequencies were 585 Hz, 1493 Hz, 2463 Hz and 3623 Hz which represented first formant, second formant, third formant and forth formant respectively. Natural speech syllable voiced /ba/ with duration of 150ms having fundamental frequency of 122 Hz and other formants frequencies were 550 Hz, 1370 Hz, 2436 Hz and 3572 Hz which represented first formant, second formant, third formant and forth formant respectively. To elicit speech evoked ABR stimuli were presented in quiet and noise condition. For noise condition, Adobe audition software was used to mix +10dB noise in both stimuli.

Stimuli were presented monaurally in right ear to preserved right ear advantage at sub-cortical level [22, 23] with the help of insert receiver (ER-3, Etymotic Research). Stimulus intensity was 80 dBnHL throughout recording session. Alternating polarity was used and repetition rate was 4.6/s. analysis windows was 213 ms with 50 ms pre/post stimulus. To elicit speech evoked response, vertical montage was used with the help of 3 Ag-AgCl electrodes. Two recording were done in order to check the consistency and reliability of the responses measured. All participants were instructed to be relaxed to reduce the muscular artifacts and to watch movie of personal choice in silent mode on another laptop during electrophysiological test. Peaks were marked for weighted-add waveform for each condition. Transient (wave V, wave A & slope of wave V/A) and sustained response of speech evoked ABR were noted from the recorded waveforms.

The recorded speech evoked brainstem responses were extracted using AEP-to-ASCII software and further analyzed in MATLAB. Frequency analysis responses were carried out which provided the information about amplitude of fundamental frequency (Fo) and various harmonics (H2, H3 & H4).

Statistical Analysis:

Shapiro-Wilk's test was performed to check the normality of data distribution and result revealed non-normal data distribution ($p < 0.05$). Henceforth, non-parametric test were involved for further statistical analysis. However, behavioral speech in noise test data was normally distributed. Hence, parametric Independent 't' test was performed for behavioral SPIN scores between two groups. Descriptive statistics was carried out to obtain mean, median and standard deviation. Mann-Whitney U test was done to compare typically developing children and children with dyslexia. Wilcoxon signed rank test was done to compare between two speech stimuli i.e. /da/ and /ba/ in each condition i.e. quiet and noise as well as between condition (quiet & noise) for each speech stimulus i.e. /da/ and /ba/. Finally, Spearman correlation analysis was done to check the relationship between different parameters of speech-evoked ABR and SPIN scores if any.

RESULTS

In typically developing children, component of speech evoked auditory brainstem response (onset and steady-state portion) were present in 12 children (92%) out of 13 children. However in children with dyslexia onset and steady-state portion of speech evoked ABR were present only for 11 children (68.75%) out of 16 children. Hence further statistical analyses were done for 12 children with normal hearing and 11

children with dyslexia.

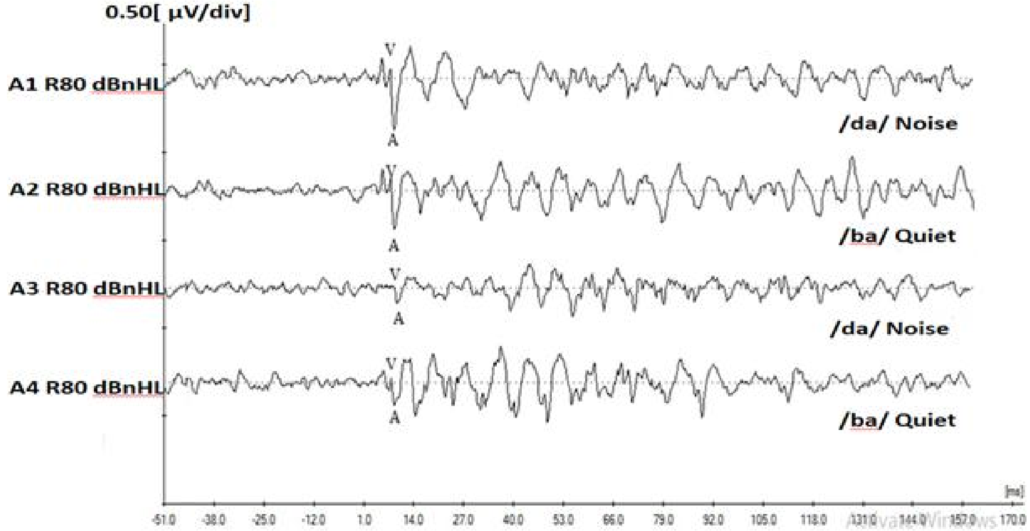

Figure 1: A sample waveform of speech-evoked ABR in a typically developing child

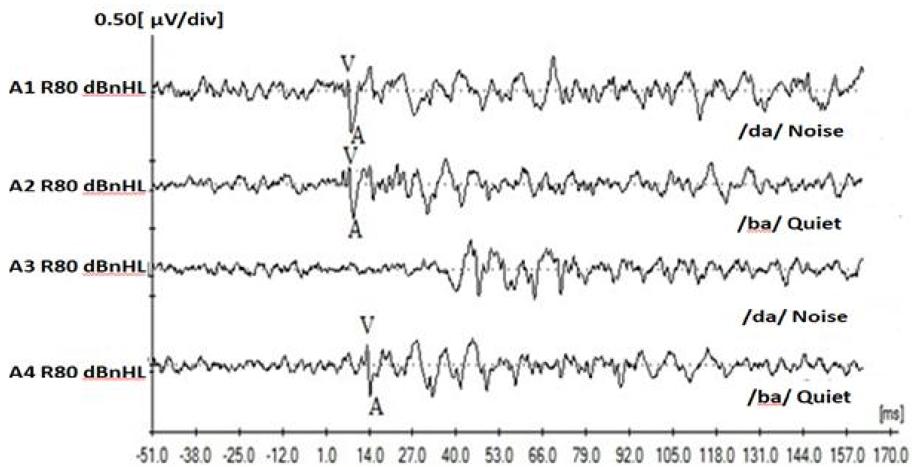

Figure 2: A sample waveform of speech-evoked ABR in children with dyslexia

Electrophysiological Measures

Speech evoked ABR were explained under two broad heading in results section i.e. onset response (Wave V, Wave A, & slope of Wave V/A) and sustained response (Fo, H2, H3 & H4) of sp-ABR.

Onset response of the speech evoked ABR

Descriptive statistics show the mean latency of wave V and wave A were longer (poorer) for children with dyslexia in comparison to typically developing children in both quiet and noise condition (figure 3). Further, the latency of wave V and wave A was prolonged (poorer) in noise condition compared to quiet in each group. In addition, standard deviation (SD) was higher for children with dyslexia compared to typically developing children which shows higher variability or heterogeneous nature of dyslexic children in both noise and quiet condition using both speech stimuli. To check the statistical significant difference between two groups in each condition for both speech stimuli, Mann-Whitney U test was done. Mann-Whitney U test results revealed that for syllable /da/ in quiet condition, there were statistical significant difference between two groups for wave V ($Z=3.97$, $p < 0.01$), wave A ($Z= 3.97$, $p < 0.01$) and slope of wave V/A ($Z=3.33$, $p < 0.01$). Further, in noise condition for speech syllable /da/ stimulus showed statistical significant difference between two groups for wave V (Z=7.00, p <0.01) and wave A (Z=4.08, p < 0.01). However, significant differences were not noticed for slope of wave V/A in spite of higher mean noticed for dyslexic children compared to typically developing children. Similarly, speech evoked ABR using /ba/ speech stimulus shows significant differences between two groups for wave V(Z=4.01, p < 0.01), wave A (Z=3.87, p < 0.01) and slope of wave V/A(Z=2.03, p < 0.01) in quiet and significant difference showed for wave V (Z=4.41, p < 0.01) and wave A (Z=4.07, p < 0.01) in noise condition as well as in noise condition except slope of wave V/A in noise condition only.

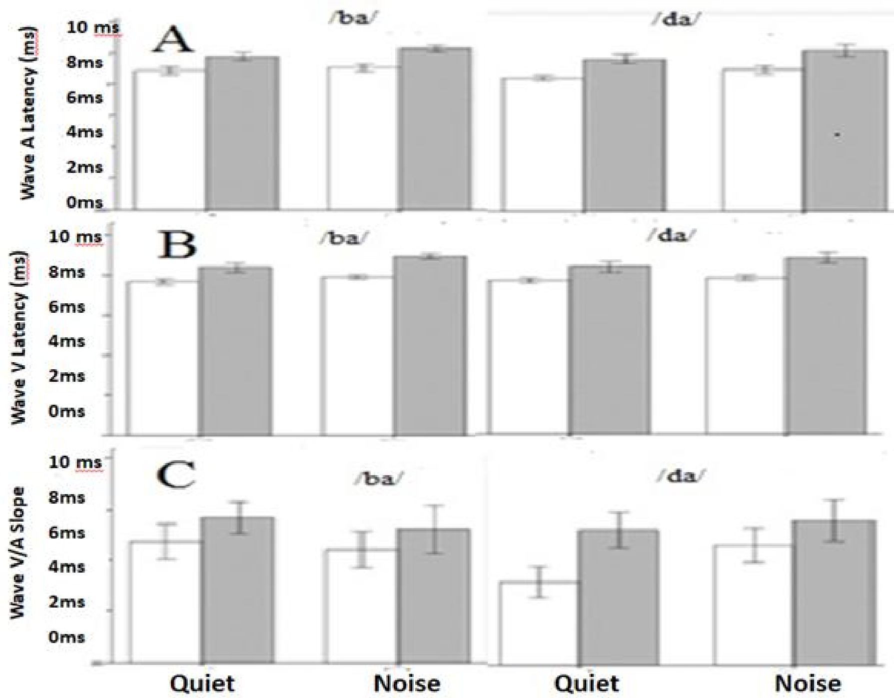

Figure 3: Mean and 95% confidence interval (CI) of syllable /da/ and /ba/ (A). for wave A latency; (B). Wave V latency; (C). Wave V/A slope ; [Note: Empty box: Typically developed children & Filled box: Dyslexic children]

Wilcoxon sign-ranked test was carried out for comparing the performance between two speech stimuli (/da/ & /ba/) in quiet and noise condition for each group i.e. typically developing children and children with dyslexia. TDC showed statistically significant difference for wave A (z-value= 2.96, p < 0.01) and slope of V/A complex (z-value = 2.96, p < 0.01) in quiet condition and only for wave V (z-value = 2.05, p < 0.05) in noise condition. In contrast, children with dyslexia did not show statistical significant differences for stimulus /da/ as well as /ba/ in both quiet as well as in noise condition. Wilcoxon sign-ranked test were also performed to compare the difference between quiet and noise condition for each speech stimulus in each group. Typically developing children shows statistically significant differences between quiet and noise conditions for both /da/ and /ba/ speech stimulus for wave V, wave A and slope of the wave V/A except slope of the wave V/A for /ba/ stimuli (z-value = 0.78). In contrast, children with dyslexia show statistically significant differences between quiet and noise condition for both the speech stimuli for wave V and wave A. However, significant differences were not noticed for the slope of the wave V/A for both the speech stimuli

Sustained response of speech-evoked ABR

Descriptive statistics shows mean values of amplitudes decreases (lesser) with increased higher harmonics. In addition, Standard deviation (SD) also decreases with increase in higher harmonics. Higher amplitude of mean was observed for fundamental frequencies in each condition for both the speech stimuli compared to other harmonics. Mann-Whitney U test were carried out to investigate the comparison between two groups and results revealed that there were no significant differences observed between two groups for both /da/ and /ba/

speech stimuli in both quiet as well as in noise conditions except H4 in quiet condition for syllable /ba/ ($z = 1.90$, $p < 0.05$). Wilcoxson sign-ranked test was carried out for comparing the performance between two speech stimuli (/da/ & /ba/) in quiet and noise condition for each group and revealed statistically significant difference for amplitude H2 (z-value = 3.05, $p < 0.01$) and H4 (z-value = 3.05, $p < 0.01$) in quiet condition only for TDC group.CWD group showed statistically significant difference for H2 (z-value = 2.75, $p < 0.01$) and H4(z-value = 2.84, $p < 0.01$) in quiet condition and for noise condition only for amplitude of H2 (z-value = 2.57, $p < 0.01$). Wilcoxson sign-ranked test were also performed to compare the difference between quiet and noise condition for each speech stimulus in each group. TDC shows statistically significant differences between quiet and noise conditions for /da/ speech stimulus for Fo (z-value = 2.27, $p < 0.05$), H2 (z-value = 2.11, $p < 0.05$) and H4(z-value = 2.43, $p < 0.01$). However, there was no statistical significant difference noticed between quiet and noise conditions for amplitude of Fo, H2, H3, and H4 for /ba/ syllable. In a similar line, children with dyslexia did not show statistically significant differences between quiet and noise condition for both the speech stimuli for Fo and different harmonics except amplitude of H4 (z-value = 2.43, $p < 0.01$) for syllable /da/.

Behavioral measure (Speech-In-Noise)

Descriptive statistics revealed lower (poorer) mean for children with dyslexia (54.18 ± 13.42) compare to typically developing children (75.63 ± 6.05). Further, the SD was also higher for the dyslexic children compared to typically developing children which indicates heterogeneity among clinical groups. In addition, Independent t-test was done to check whether the differences in mean scores between two groups were statistically significant or not. Results revealed significant difference between typically developing children and children with dyslexia ($t=4.83$; $p < 0.05$).

Correlation between electrophysiological and behavioral measure

Spearman correlation analysis shows negative relationship between wave V and wave A with speech perception in noise for /da/ and /ba/ in quiet and noise condition except /ba/ sound in noise condition though it was not statistically significant. The sustain responses i.e amplitude of Fo show positive relationship with SPIN for quiet and noise using both speech stimuli though not statistical significant except /da/ syllable in quiet. Similarly the amplitude of harmonics i.e. H2 and H4 showed positive relationship with SPIN though not statistically significant except /ba/ syllables in quiet for H2 harmonics. The above negative relationship reflects as latency of wave V and wave A is increasing (prolonged) the speech perception in noise reduces (poorer). Similarly, positive relationship shows as amplitude of harmonics is reducing the speech perception in noise reduces (poorer) in children with dyslexia.

DISCUSSION

Onset and sustained response of speech-evoked ABR

The finding of present study shows prolonged latencies of onset response (wave V and wave A) of speech-evoked ABR for children with dyslexia in comparison to typically developing children in quiet as well as in noise. Further, there were prolonged latency for wave V and wave A in noise condition compared to quiet condition for both /da/ and /ba/ speech stimuli. The slope of V/A complex showed statistically significant difference for both syllables in quiet condition but there were no differences observed in noise condition. Sustained portion response showed decreased (poorer) amplitudes with increased higher harmonics and concluded that background noise had merely impact on sustained response.

Prolonged latencies of onset response (wave V and wave A) of speech evoked ABR in the presence of background noise were reported in many studies [15, 16, 24-30]. speech evoked ABR in presence of noise could able to trace the subtle changes at the brainstem level among learning impaired children which could not be traced with simple click stimuli [26]. Probably poor temporal resolution ability in children with learning impairment could be due to the corticofugal modulation of sub-cortical activity which leads to neural deficits [31,32].

Individuals with learning disability show higher internal noise in the brain which reduces their ability to encode of fundamental frequency and makes difficult for individuals to exclude external noise and hence degraded response seen in children with learning impairment [33]. Johnson et al. 2007 [34] observed stimulus-latencies pattern of different speech stimuli as /ga/ < /da/ < /ba/ for sub-cortical potential. Minor peaks of speech evoked ABR provides precise information of spectro-temporal changes which occurs in formant structure and major peaks gives insight of onset response and endpoints. The detrimental effect of background noise on brainstem response leads to delayed transition period which relates to speech perception ability in noise. Overall, present study reported poorer representation of the onset responses in dyslexic children in comparison to typically developing children which indicated neural processing deficit at sub-cortical level.

Behavioral Measurement (Speech in noise test)

The present study showed statistically

significant difference between children with dyslexia and typically developing children (TDC) in speech perception in noise test. Children with dyslexia had lesser (poorer) mean scores in comparison to TDC at 0 dB SNR. The finding is supported by several studies mentioned in literature [8-10,19, 28, 35-36] . Poor performers on HINT and reading skills showed auditory based deficit [28]. Reduced temporal resolution ability in individuals with language based impairment is also reported in literature [5,19,23,36]. In addition, six-talker babble has more impact on speech perception ability in noise than two-talker since it resembles more with realistic day-to-day life situation [26]. Children with reading disorder or learning impairment who performed better on HINT task had better stop-consonant differentiation ability than those who performed poorly in hearing in noise test [23]. These perceptual deficit in noise in dyslexic children despite normal perception in quiet condition which probably indicating that the deficit may be located in central region. Due to centrally located noise induced deficit among dyslexic children showed atypical brainstem responses to speech sounds in presence of noise [8]. Overall the above finding reflects deficits in higher centers in children with dyslexia due to which the speech perception in noise is poorer compared to TDC.

Correlation between speech evoked ABR and speech in noise test

The present study showed negative correlation between latency of wave V and wave A of speech evoked ABR and SPIN scores in children with dyslexia in both conditions. The above relationship indicates as latency of the wave V and A will be prolonged the SPIN scores will be reducing (poorer) in dyslexic children and vice versa. Further, present study reported positive relationship between amplitude of fundamental frequency and other harmonics with speech in noise test though it was not statistically significant. Researchers observed an individual who performs poor on behavioral task which assess speech perception ability in noise (either HINT and/or QuickSIN) also showed prolonged latencies of onset response [16, 24-25, 27] and poor performance on behavioral task of speech perception in noise and its correlation with electrophysiological measures can give indication of learning impairment [11]

Conclusion

The finding of present study showed that speech evoked ABR can be successfully elicited with the help of natural speech syllable with long duration. Further it can be concluded that there is more need to do research by using natural speech syllable with different duration and its correlation among various behavioral tests which can tap different domain of auditory processing in clinical population.

REFERENCES

Shaywitz, E.S. & Shaywitz, A.B. (2003). Dyslexia: specific reading disability. Language-Cognition ,24(5), 147-153

Ramus., Rosen., Dakin., Day., Castellote., White., & Frith. (2003). Theories of developmental dyslexia: Insights from a multiple case study of dyslexic adults. Brain, 126, 841-865

White-Schwoch, T., & Kraus, N. (2013). Physiologic discrimination of stop consonants relates to phonological skills in pre-readers: a biomarker for subsequent reading ability. Frontiers in Human Neuroscience, 7(12), 899.

McArthur, G.M., Bishop, D.V., (2001). Auditory perceptual processing in people with reading and oral language imapirments: current issues and recommendation. Dyslexia, 7(3), 150-170

Anderson, S., Skoe, E., Chandrasekaran, B., Zecker, S., & Kraus, N. (2010). Brainstem correlates of speech-in-noise perception in children. Hearing Research, 270(1-2), 151-157.

Dole, M., Hoen & Meunier, F. (2012). Speech-in-noise perception deficit in adults with dyslexia: effects of background type and listening configuration. Neuropsychologia, 50(7), 1543-552

Ziegler, J.C., Pech-Georgel, C., George, F., Alario, F.X., &Lorenzi, C. (2005). Deficits in speech perception predict language learning impairment. ProcNatlAcadSci U S A 102, 14110 -14115.

Ziegler, J.S., Pech-Georgel, C., George, F., Lorenzi, C. (2009). Speech-perception-in-noise deficits in dyslexia. Developmental Science, 12, 732-745.

Zeigler, J.C., Pech-Georgel, C., George, F. & Lorenzi, C. (2011). Noise on, voicing off: Speech perception deficit in children with specific language impairment. Jounal of experimental child psychology, 110(3), 362-372

Bradlow, A.R., Kraus, N., & Hayes, E. (2003). Speaking clearly for children with learning disabilities: sentence perception in noise. Journal of Speech Language Hearing Research, 46, 80 -97.

White-Schwoch, T., Woodruff Carr, K., Thompson, E. C., Anderson, S., Nicol, T., Bradlow, A. R., … Kraus, N. (2015). Auditory processing in noise: A preschool biomarker for literacy. PLoS Biology, 13(7), 1-17.

Cohen-Mimran R, Sapir S (2007). Auditory temporal processing deficits inchildren with reading disabilities. Dyslexia,13, 175-192.

Warrier, C. M., Johnson, K. L., Hayes, E., Nicol, T., & Kraus, N. (2004). Learning impaired children exhibit timing deficits and training-related improvements in auditory cortical responses to speech in noise. Experimental Brain Research. Experimentelle Hirnforschung. Experimentation Cerebrale, 157(4), 431-441.

Billings, C. J., Tremblay, K. L., Stecker, G.C., & Tollin, W.M. (Human evoked cortical activity to signal-to-noise ratio and absolute signal level. Hearing Research, 254, 15-24

Cunningham, J., Nicol, T., Zecker, G. S., Bradlow, A., & Kraus, N. (2001). Neurobiologic responses to speech in noise in children with learning problems: deficits and strategies for improvement. Clinical Neurophysiology, 112(5), 758-767.

Russo, N., Nicol, T., Musacchia, G., & Kraus, N. (2004). Brainstem responses to speech syllables. Clinical Neurophysiology, 115(9), 2021-2030.

Anderson, S., Chandrasekaran, B., Yi, H. G., & Kraus, N. (2010). Cortical-evoked potentials reflect speech-in-noise perception in children. European Journal of Neuroscience, 32(8), 1407-1413.

Hornickel, J., & Kraus, N. (2013). Unstable Representation of Sound: A Biological Marker of Dyslexia. Journal of Neuroscience, 33(8), 3500-3504. -

Anderson, S., Skoe, E., Chandrasekaran, B., & Kraus, N. (2010). Neural Timing Is Linked to Speech Perception in Noise. The Journal of Neuroscience, 30(14), 4922-4926.

American National Standard Institute. (1991). American National Standard Maximum Permissible Ambient Noise Level for Audiometric Test Rooms. ANSI S3.1-1991. New York: American National Standard Institute.

Yathiraj, A., Vanaja, C.S., Muthuselvi, T.(2009). Maturaration of auditory processing in children aged 6-10 years. AIISH research fund project. AIISH

Sinha, S.K., & Basavaraj, V. (2010). Speech evoked auditory brainstem response: a new tool to study brainstem encoding of speech sounds. Indian Journal of Otolaryngology and Head & Neck Surgery, 62(4), 395-399.

Hornickel, J., Skoe, E., & Kraus, N. (2009). Subcortical laterality of speech encoding. Audiology and Neurotology, 14(3), 198-207.

Banai, K. (2005). Brainstem Timing: Implications for Cortical Processing and Literacy. Journal of Neuroscience, 25(43), 9850-9857.

Wible, B., Nicol, T., & Kraus, N. (2005). Correlation between brainstem and cortical auditory processes in normal and language-impaired children. Brain, 128(2), 417-423.

Song, J. H., Banai, K., Russo, N. M., & Kraus, N. (2006). On the relationship between speech- and nonspeech-evoked auditory brainstem responses. Audiology and Neurotology, 11(4), 233-241.

Banai, K., Abrams, D., & Kraus, N. (2007). Sensory-based learning disability: Insights from brainstem processing of speech sounds. International Journal of Audiology, 46(9), 524-532. .

Anderson, S., Parbery-Clark, A., Yi, H.-G., & Kraus, N. (2011). A neural basis of speech-in-noise perception in older adults. Ear and Hearing,32(6), 750-7.

Hornickel, J., Chandrasekaran, B., Zecker, S., & Kraus, N. (2011). Auditory brainstem measures predict reading and speech-in-noise perception in school-aged children. Behavioural Brain Research, 216(2), 597-605.

Chandrasekaran, B., Hornickel, J., Skoe, E., Nicol, T., & Kraus, N. (2009). Context-Dependent Encoding in the Human Auditory Brainstem Relates to Hearing Speech in Noise: Implications for Developmental Dyslexia. Neuron, 64(3), 311-319.

Johnson, K. L., Nicol, T. G., Zecker, S. G., & Kraus, N. (2007). Auditory brainstem correlates of perceptual timing deficits. Journal of Cognitive Neuroscience, 19(3), 376-85.

Song, J. H., Skoe, E., Banai, K., & Kraus, N. (2011). Perception of speech in noise: neural correlates. Journal of Cognitive Neuroscience, 23(9), 2268-2279.

Sperling, A.J., Zhong-Lin, L., Manis, F.R., Seidenberg, MS., (2005). Deficits in perceptuual noise exclusion in developmental dyslexia. Neuroscience, (8), 862-863

Johnson, K. L., Nicol, T., Zecker, S. G., Bradlow, A. R., Skoe, E., & Kraus, N.

(2008). Brainstem encoding of voiced consonant-vowel stop syllables. Clinical Neurophysiology, 119(11), 2623-2635.

Hornickel, J., Skoe, E., Nicol, T., Zecker, S., & Kraus, N. (2009). Subcortical differentiation of stop consonants relates to reading and speech-in-noise perception. Proceedings of the National Academy of Sciences of the United States of America, 106(31), 13022-7.

Song, J. H., Nicol, T., & Kraus, N. (2011). Test-retest reliability of the speech-evoked auditory brainstem response. Clinical Neurophysiology, 122(2), 346-355.