European Archives of Oto-Rhino-Laryngology (2023) 280:2099–2118
https://doi.org/10.1007/s00405-023-07830-3

REVIEW ARTICLE

Speech auditory brainstem response in audiological practice: a systematic review

Meliha Basoz Behmen[1] · Nilsu Guler[1] · Elif Kuru[1] · Nilufer Bal[1] · Ozge Gedik Toker[1]

Received: 25 December 2022 / Accepted: 7 January 2023 / Published online: 18 January 2023

Abstract

Background Speech-ABR is an auditory brainstem response that evaluates the integrity of the temporal and spectral coding of speech in the upper levels of the brainstem. It reflects the acoustic properties of the stimulus used and consists of seven major waves. Waves V and A represent the onset of the response; wave C transition region; D, E, and F waves periodic region (frequency following response); and wave O reflects the offset of the response.

Purpose The aim of this study is to evaluate the clinical availability of the speech-ABR procedure through a literature review.

Methods Literature search was conducted in Pubmed, Google Scholar, Scopus and Science Direct databases. Clinical studies of the last 15 years have been included in this review and 60 articles have been reviewed.

Results As a result of the articles reviewed, it was seen that most of the studies on speech ABR were conducted with children and young people and generally focused on latency analysis measurements. Most used stimulus is the /da/ syllable.

Conclusions Speech ABR can objectively measure the auditory cues important for speech recognition and has many clinical applications. It can be used as a biomarker for auditory processing disorders, learning disorders, dyslexia, otitis media, hearing loss, language disorders and phonological disorders. S-ABR is an effective procedure that can be used in speech and language evaluations in people with hearing aids or cochlear implant. It may also be of benefit to the aging auditory system's ability to encode temporal cues.

Keywords Speech ABR · Speech evoked auditory brainstem response · S-ABR · Central auditory processing

Introduction

Neural encoding of speech sound begins in the auditory nerve and travels to the auditory brainstem. Recording of auditory brainstem responses (ABR) has been recognized as a valid and reliable tool to assess the integrity of neural transmission of acoustic stimuli [1]. When verbal stimuli are used in the ABR assessment, potential information can be obtained about how the verbal stimulus is processed in the brainstem and which structures are involved in this process. Speech Auditory Brainstem Response (speech-ABR/s-ABR) is electrophysiological potentials that reflect the onset, displacement, and periodicity of the stimulus [2]. In speech ABR protocols, syllables consisting of various consonant and vowel combinations (CV) are used as stimuli [3]. Commonly used CV (consonant–vowel) stimuli are 40 ms or 170 ms /da/, /ba/, and /ga/ [2]. The spectral distributions of brainstem responses to these syllables are different [3]. Speech ABR represents the acoustic properties of the consonant (temporary component) and vowel (periodic component) in the stimulus and reflects neural encoding [1, 3, 4]. The computer-synthesized /da/ syllable designed by Nina Kraus is the best known and frequently used s-ABR stimulus [3, 5]. After stimulation with the /da/ combination, a response occurs, characterized by seven wave peaks, designated V, A, C, D, E, F, and O waves, respectively [1, 3, 6]. Figure 1 shows the s-ABR responses evoked by the 40 ms

✉ Elif Kuru
ekuru@bezmialem.edu.tr

Meliha Basoz Behmen
mbasoz@bezmialem.edu.tr

Nilsu Guler
nillgulerr@gmail.com

Nilufer Bal
nibal@bezmialem.edu.tr

Ozge Gedik Toker
ogedik@bezmialem.edu.tr

[1] Department of Audiology, Health Sciences Faculty, Bezmialem Vakif University, Istanbul, Turkey

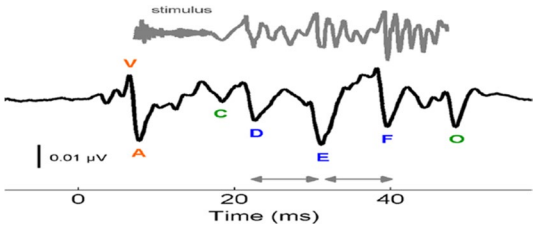

Fig. 1 Display of 40 ms /da/ stimulus (gray) and responses (black) [3]

/da/ syllable and its similarity to the acoustic properties of the stimulus.

S-ABR responses can be analyzed in two parts. The temporal part consists of V, A, C, O waves and contains responses to the acoustic filter properties of the syllable. Waves V and A appear with the onset of the consonant and reflect the onset of the stimulus. It occurs in the first 10 ms and is similar to the click stimulus auditory brainstem response. The negative C wave reflects the consonant-to-vowel stimulus transition region. Continuous part consists of D, E, and F waves and is called the Frequency Follow Response (FFR). The FFR reflects the harmonic nature of the stimulus and records phase-locked neural activity to periodic information within the stimulus. The negative O wave is the response to cessation, and it reflects the offset of the stimulus [1, 3, 7, 8].

The ascending auditory pathways between the cochlear nerve and the midbrain are predominantly active in the generation of waves in the temporal part. More specifically, the V–A complex reflects auditory processing in the upper part of the brainstem [7, 8]. Although the FFR is produced from many brainstem regions, including the cochlear nucleus, superior olivary complex, lateral lemniscus, and inferior colliculus, the main generating region is the inferior colliculus [7].

In spectral analysis measurements, the F_0 (fundamental frequency) wavelength corresponds to the time between the D, E, and F waves. F_0 contains non-linguistic information, such as gender and emotion. The range of small, higher frequency fluctuations between these waves corresponds to the F1 (first formant) frequency of the stimulus. F2 (second formant) is an important acoustic cue to identify linguistic content. However, F2 and higher formants in the /da/ stimulus are beyond the phase locking limit of the rostral brainstem [1, 9]. The most frequently used parameters in S-ABR protocols are specified as under the control of BioMARKTM software, alternate polarity, 10.9/ms rate, 70–85 ms analysis window, 60–85 dB SPL stimulus intensity, monaural stimulation, and 4000–6000 sweeps. During the test, the patient should remain quiet and relaxed, so the patient may be allowed to watch a movie with reduced volume or subtitles [5].

Latency (ms) measurements are about the sensitivity to which brainstem nuclei respond simultaneously to acoustic stimuli; amplitude (µV) measurements give information about how strong the response of brainstem nuclei to acoustic stimuli. The slope (µV/ms) and area (µV × ms) values of the VA complex are calculated by measuring the latency and amplitude of the VA complex. VA complex measurements provide information about the timing of neuronal discharges [10].

It is known that the test is indicated for neurological and mental conditions and changes in hearing, language, and learning [11]. S-ABR could potentially reflect higher order auditory functions and the effects of dysfunctions on the lower brainstem [12, 13]. Understanding the neural processing of speech sounds at the brainstem level provides insight into the central auditory processes involved in normal hearing subjects as well as in clinical populations [11]. S-ABR seems well-suited to provide objective physiological information about speech coding in the auditory pathway, especially in populations with known defects at the perceptual and cognitive levels [2].

The aim of this study is to put together clinical studies and results on speech ABR through a review of the literature of the last 15 years, and ultimately to evaluate the clinical usability of s-ABR.

Methods

Literature review was conducted in Pubmed, Google Scholar, Scopus and Science Direct databases for “speech ABR”, “ABR-speech”, “speech evoked ABR”, “speech evoked auditory brainstem response”, “speech evoked auditory brainstem responses”, “speech stimuli ABR”, “speech stimulus ABR”, “ABR types”, “s-ABR” keywords.

Inclusion criteria are studies of the last 15 years, written language in English, human studies, clinical studies in individuals with normal peripheral hearing, pathologies affecting the hearing system, cochlear implant or hearing aid users. There is no restriction on age groups in this study. The exclusion criteria are animal studies, the lack of written language in English, literature reviews, case studies, thesis studies, studies on s-ABR parameters, studies on factors affecting s-ABR, studies on s-ABR neural regions.

7774 search results and 1662 studies on s-ABR were found. The titles and abstracts of 332 articles were read and 272 of them were eliminated. 60 articles that met the inclusion criteria were reviewed. The article selection process is shown in Fig. 2.

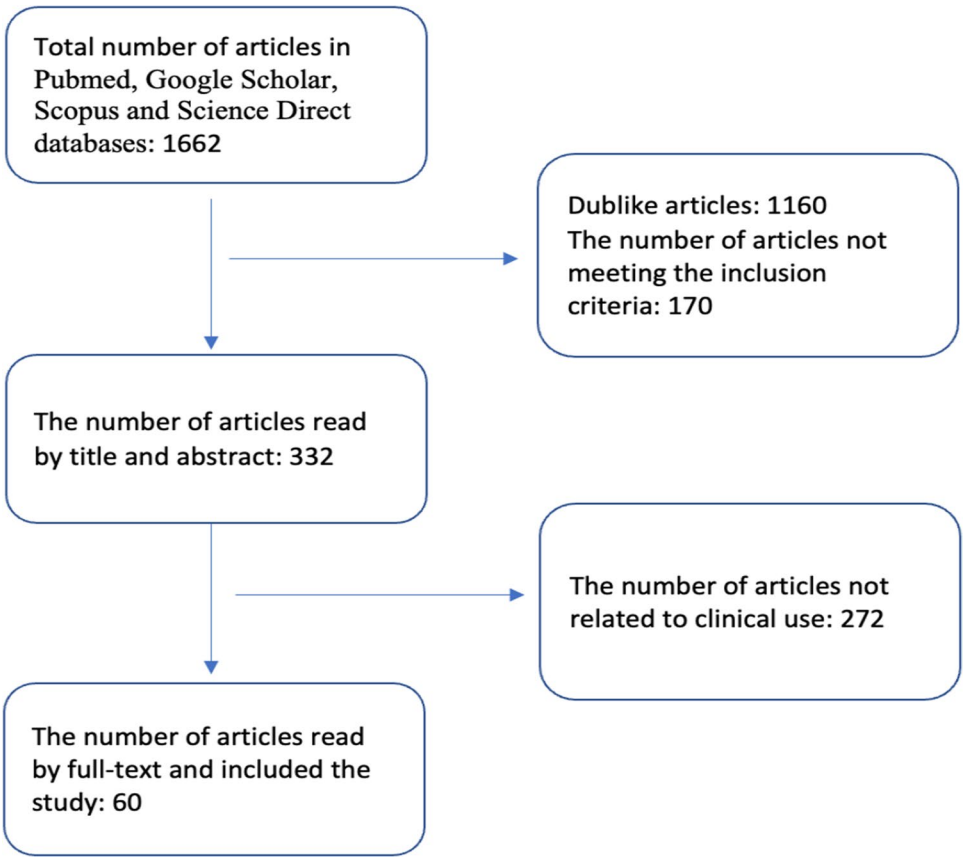

Fig. 2 Flowchart of articles through screening and selection process

Results

The table summarizing the reviewed articles (Appendix 1) is given in the appendices.

Speech-ABR in normal hearing

In s-ABR studies in typically developing children and adults with normal peripheral hearing, waves were found to be reliably present in all subjects [14–23]. Sanfins et al., obtained wave analysis measurements with 40 ms /da/ stimulus in children and adolescents whose native language is Brazilian Portuguese, similar to adults [19]. Karawani and Banai obtained responses in native Arabic and Hebrew adults consistent with other studies and reported that brainstem processing of the /da/ syllable did not differ between English speakers and speakers of Semitic languages, such as Arabic and Hebrew [17]. Lee and Han found that syllabic stimuli formed with 9 Korean explosive consonants have a clear and distinguishable morphology, but the wave latencies are slightly longer than those for the /da/ stimulus [16]. Results obtained from studies using the /da/ syllable are generally consistent with each other [15, 17, 19, 24]. Only Sanfins et al., reported different latency values with the /da/ syllable in children and adolescents whose mother tongue is Italian [25].

Pinto and Martinelli obtained wave morphology like adults in neonates with normal hearing and no auditory risk factors but observed longer latency and greater amplitude variation in the waves analyzed. While V, A waves and VA complex were obtained in all newborns, D, E, F waves were obtained in more than 88% and C waves in only 75% [24].

Vander Werf and Burns observed that the amplitudes of the s-ABR onset and offset components were significantly reduced and the F, O wave latencies were prolonged in elderly individuals. He also reported that the amplitude and morphology of the waves are slightly more variable in older individuals, and that the C wave may not be identified even when other waves are reliable [26]. Based on these, it is thought that s-ABR may provide information about the ability of the aging auditory system to encode temporal cues [26].

In comparisons of click and s-ABR in typically developing individuals, s-ABR wave latencies were found to be longer than those obtained in click-ABR [14, 15, 24]. Karawani and Banai found a correlation between click-ABR and s-ABR V, A waves [17]. Pinto and Martinelli reported that speech stimulus latency in newborns is longer than click stimulus, but the responses are very similar [24].

Sinha and Basavaraj and Rana and Barman observed that the amplitude of the fundamental frequency F_0 is greater than F_1 in their spectral analysis measurements [15, 23]. It has been reported that the fundamental frequency has a greater energy, better phase locking, and is coded more robustly than its harmonics [15].

S-ABR test–retest studies show that responses are reliable and reproducible over months [18, 20, 21]. Hornickel et al. reported that s-ABR responses in typically developing children were reproducible and consistent over one year of growth [20]. Zakaria and Jalaei observed that there was no significant difference in latency, amplitude, and VA complex measurements between the two sessions in children tested at a lower intensity level (30 dB SL) 3 months apart [21]. Song et al. achieved a high degree of test–retest reliability for s-ABR responses recorded with the /da/ stimulus in quiet and noisy conditions [18].

It has been reported that the inclusion of the S-ABR test in the clinical battery with OAE (otoacoustic emission) tests may be more effective [22, 23]. Dhar et al. found that DPOAE (distortion product OAE) is correlated with s-ABR harmonics, envelope boundary and spectrotemporal directions [22]. Rana and Barman reported a correlation between TEOAE (transiently evoked OAE) and s-ABR onset responses [23].

Lotfi et al. and Moossavi et al. reported that s-ABR responses recorded in the presence of contralateral noise in individuals with normal hearing can enable to evaluate the performance of the rostral part of the auditory efferent system [27, 28].

Speech-ABR in auditory processing disorders

The S-ABR has proven to be a valid method for assessing brainstem auditory function in individuals with auditory processing disorder (APD) [12, 29–32]. Rocha-Muniz et al. observed that 23 of 27 children with abnormal s-ABR responses had APD and reported that a child with abnormal s-ABR responses had an 85.15% probability of observing an abnormal behavioral assessment of auditory processing [30].

The s-ABR can make a clear distinction between children at risk for central APD (CAPD) and typically developing children [31]. Children with CAPD have great difficulty distinguishing stimuli based on temporal cues [32]. Studies have found that abnormalities are mostly in the temporal part [12, 29–32]. Kumar and Singh observed weak wave morphology, prolonged V and A wave latencies, decreased V/A slope, high Biomark scores and decreased F_1 amplitude in children at risk for CAPD without reading disorders [31]. Flippini and Schochat found prolonged V, A waves and VA complex latencies, low A, C, F waves amplitude, and low V/A slope [29]. Rocha-Muniz et al. observed prolonged V, A latencies, too and reported 68% specificity, 80% sensitivity, and 74% accuracy for wave A latency in children with APD [12].

Filippin et al. found that the latencies of children with APD increased in the presence of background noise compared to the quiet environment, and the wave latencies in the background noise decreased after 8 weeks of formal auditory training. This study shows that the effectiveness of auditory training can be evaluated by s-ABR recorded in background noise [33].

Speech ABR in language disorders, phonological disorders and stuttering

In studies, children with Language Disorders (LD) showed abnormalities in both temporal and spectral frequency encoding measures [32–34]. Individuals with CAPD have more widespread impairment and have additional difficulty distinguishing speech harmonics [32]. Rocha-Muniz et al. observed prolonged V, A, C, E, F, O wave latencies and double peaks for the wave A [32]. Gabr and Darwish reported prolonged A, C, D, E, F, O wave latencies, decreased amplitudes, and prolonged VA complex latency, decreased VA amplitude and slope [34].

Rocha-Muniz et al. evaluated the sensitivity of s-ABR and reported the highest sensitivity values in children with LD [12]. S-ABR is considered an easy, fast, reliable and procedure that allows for the early diagnosis and intervention of language disorders [34]. Filippin et al. observed a prolongation of latencies and a decrease in amplitudes in the presence of background noise in children aged 7–13 with LD, while they observed a decrease in latencies and an increase in amplitudes after 8 weeks of auditory training. This study demonstrates that the s-ABR procedure recorded in the presence of background noise can be used to evaluate auditory training effectiveness in children with LD [33].

Children with phonological disorders (PD) have functional impairment in speech processing in the brainstem region and changes in the physiological mechanisms of speech [35, 36]. Gonçalves et al. found weaker morphology and prolonged latencies for V and A waves in children with PD [35]. El-Beltagy et al. observed a prolongation of transient and permanent part latencies, while obtaining well-defined and reproducible responses [36]. There are no abnormalities in wave amplitudes and VA measurements [35, 36]. Gonçalves et al. revealed that the sensitivity of detecting phonological disorders for s-ABR is 56% and the specificity

is 94%. He reported that abnormal coding of speech sounds may be a biological marker of phonological disorders but cannot identify the biological origins of phonological problems [35]. El-Beltagy et al. reported that cortical auditory processing can be evaluated with s-ABR and MMN in these children [36].

It has been reported that children and adults who stutter have insufficient neural encoding for temporal features in the early stages of the auditory pathway, and this may be the reason for their inability to speak fluently [37, 38]. Tahaei et al. observed latency prolongations in onset and offset waves and reduced VA slope for s-ABR in Persian native stuttering adults [37]. Crivellaro Gonçalves et al., on the other hand, found that especially the C wave and VA complex latency were prolonged, and the amplitude of the VA complex increased in stuttering children whose native language was Brazilian Portuguese [38]. No abnormality was observed in spectral analysis measurements [37, 38].

Speech ABR in learning disorders and dyslexia

Inadequate encoding of speech signals in the brainstem has been reported in children with language-based learning problems [39–43]. In addition, weakened correlation between the brainstem and auditory cortex have been found in such children [39]. The s-ABR is an effective tool to identify underlying auditory processing difficulties in children with learning disabilities and may be helpful in early intervention [41].

Malayi et al. compared click ABR and s-ABR responses in children with learning disabilities (LD) and reported delays in both the click and s-ABR temporal components for children with LD [42]. In contrast, Song et al. reported that click and s-ABR reflect separate neural processes, and that only processes related to encoding complex signals, such as speech, are impaired in children with LD [43]. In both studies, prolongation was observed especially in the latency of V, A waves and V–A complex [42, 43]. Ghannoum et al. found prolonged latency for V, A, F, C, D waves and decreased amplitudes for D, E, C, F waves in children with LD compared to normal children [40]. Sachin et al. reported prolongation of V, B, E wave latencies and decreased V, B, C, D, E wave amplitudes [41].

In a study by Billiet and Bellis it was shown that 37.5% of children with dyslexia have abnormal brainstem timing with s-ABR. Children with dyslexia with abnormal brainstem timing have prolongation of all s-ABR wave latencies and abnormal VA slope [44]. Kouni et al., in a study conducted with sequential /ba-ba/ stimulus in native Greek-speaking adults with dyslexia, prolonged A and C wave latencies and A–C interwave latency were obtained [45]. Kouni et al. used the /ma/ stimulus to assess young adults with dyslexia and obtained longer-than-normal latency for initial responses [46]. In addition, Kouni et al. reported that latency prolongation in adults with dyslexia is greater than that in individuals with other learning disabilities [45].

Billiet and Bellis found that six children with abnormal s-ABR responses did not meet the diagnostic criteria for CAPD in their study which they evaluated the central auditory function with behavioral tests of dyslexic children with normal and abnormal s-ABR responses. Therefore, they reported that the s-ABR can identify a subset of children who do not meet the diagnostic criteria for CAPD with behavioral tests of central auditory assessment but could benefit from auditory-based intervention approaches and should be included in the central auditory test battery [44].

On the other hand, Hornickel and Kraus revealed that poor readers have more variable s-ABR responses than average and good readers, and this is a biomarker of dyslexia [47].

Speech ABR in autism spectrum disorder and attention deficit hyperactivity disorder

Poor neural synchronization in speech stimulus processing has been observed in studies of children with autism spectrum disorder (ASD) [48–51]. In general, subcortical transcription of voice is widely impaired in these individuals [50]. Ramezani et al. and Russo et al. reported that children with ASD obtained prolonged latencies for all s-ABR waves, although normal ABR responses were present with a click stimulus. Although it was observed that the initial waves (V, A) and the offset wave (O) had longer latency, generally no abnormality was observed in the spectral analysis measurements and wave amplitudes [48, 50]. Russo et al. found significantly prolonged D and F wave latencies in silence and reduced amplitude for the F wave in background noise in s-ABR assessment in quiet and background noise [50]. Kamita et al., on the other hand, obtained a shorter wave V latency in those with ASD and stated that the initial part of the verbal stimulus may have faster neural encoding, which may cause hypersensitivity to complex sounds, such as speech. Other wave latencies and VA measurements are not abnormal [49].

Chen et al. reported that the V wave latency was shortened significantly, and the amplitudes of the A and C waves increased, in the s-ABR evaluation they performed in two different time periods (10 months apart) in preschool children with ASD. While the V and A wave latencies were

longer in the first test, it was observed that the F wave latency was prolonged, and the E wave amplitude decreased in the second test. This study also showed that subcortical level auditory processing in children with ASD is impaired and still immature compared to typically developing children of the same age [51]. It is thought that abnormal speech processing at the brainstem level may have a significant effect on language impairment in preschool children with ASD. It has been reported that s-ABR can be used as an objective tool for evaluating children's language performance and the effectiveness of auditory rehabilitation programs in this patient group [48, 51].

It has been emphasized that children with attention deficit hyperactivity disorder (ADHD) may have problems in auditory brainstem timing and information processing in the cortex [52, 53]. Azzam and Hasan revealed that 87% of children with ADHD have abnormal s-ABR responses. In particular, the V, A, C, and VA complex latencies of the initial responses are significantly prolonged, but there is no abnormality in the wave amplitudes [52]. Jafari et al. observed prolonged latencies for the A, D, E, F, O, and VA complex in children with ADHD [53]. Azzam and Hasan achieved abnormal ABR responses to the click stimulus in only 33% of children with ADHD [52]. In contrast, Jafari et al. observed diffuse dysfunction in processing click and speech stimuli at the brainstem level in these children [53]. It has been reported that S-ABR can be used as a biomarker for neural asynchrony in the brainstem in ADHD [52, 53].

Speech ABR in hearing loss

Peixe et al. revealed that speech-ABR can be applied in people with hearing loss, and it is not much affected by peripheral hearing loss, unlike click stimulus [54]. Korawand et al. observed prolonged D, E wave latencies and increased offset (O) wave amplitude in children with mild to moderate sensorineural hearing loss (SNHL) [55]. Leite et al., on the other hand, observed a prolongation of the V, A and O wave latencies in this group [56]. Jalaeia and Zakariab reported that children with bilateral moderate SNHL have prolonged V, A, C wave latencies and a steeper VA slope, but continuous components and O wave are not affected by hearing loss [57].

Nada et al. in their study with /da/ and /ba/ stimuli revealed that the initial responses were more affected by the continuous part, and while the V, A, C, F wave latencies were elongated, no abnormality was observed in the amplitudes in adults with mild to moderate SNHL [58]. Peixe et al. observed only prolongation of C wave latency in adults with moderate SNHL [54]. Abd El-Ghaffar et al. observed prolongation in V, A wave latencies and deterioration in F_0 amplitude (pitch coding) in the presence of noise in adults with unilateral hearing loss (UHL). Therefore, it has been reported that individuals with UHL may confuse temporal phonemes, have deficiencies in understanding rapid speech and speaking and listening skills in background noise [59]. Anderson et al. reported that adults with mild-to-moderate hearing loss may have difficulties in understanding speech in background noise due to impaired balance of envelope-to-fine structure [60].

Children with childhood otitis media (OM) have impaired speech coding in the brainstem [61, 62]. Sanfins et al. observed prolongation of latency, especially in the initial responses (V, A waves), but reported that there was no abnormality in amplitudes in children who had secretory otitis media in the first 6 years of their lives and underwent myringotomy for bilateral ventilation tube placement [61]. Al-Kabarity et al. observed prolongation of V, A, O wave latencies and decreased VA slope in children with OM with long-standing effusion [62].

Speech ABR in hearing aid and cochlear implant users

Speech-ABR has been reported to have clinical application potential as an objective measure of speech perception with hearing aids [56, 63–65]. Leite et al. observed a significant decrease in wave V, A, O latencies after 9 months of hearing aid use of children with mild to moderate SNHL but revealed that wave O latency was longer than normal. This study shows that hearing aid use causes neuroplasticity in the central auditory pathways, but the offset component takes longer to mature [56]. BinKhamis et al. reported that aided responses had shorter latency, greater amplitude, and better F_0 coding than non-aided responses [63]. Consistent with this study, Shetty et al. reported that good hearing aid users have better F_0 coding at the brainstem level than poor hearing aid users [64].

Hassan et al. in their s-ABR study in people with cochlear dead regions with spectral maxima stimuli after long-term use of hearing aids, observed longer latency and smaller amplitude in dead regions. Thus, it was revealed that the brainstem can encode speech signals with perpendicular spectral maxima to the cochlear dead regions in long-term HA users, and this can be explained by the neuroplasticity of the auditory system [65].

Bellier et al. in their study in which they recorded the responses to 180 ms /ba/ stimulus directly via hearing aids or insert earphones using a wireless connection, they reported hearing aid stimulation provided high quality responses

without any stimulus artifact and gave as good results as insert earphones for the same stimulation level. It has been demonstrated that s-ABR with direct hearing aid stimulation is reliable for evaluating both envelope and spectral characteristics [66].

In addition, speech ABR can be applied as a routine and reliable test for postoperative language and speech assessment protocols in cochlear implant programming [67, 68]. Gabr and Hassaan and Jarollahi et al. showed that cochlear implant users have longer-than-normal latencies, although s-ABR responses are present. It has been reported that individuals with cochlear implants have neural encoding deficiencies in the temporal and spectral areas at the level of the brainstem [67, 69]. Rahman et al. observed a decrease in V, F, O wave latencies as the duration of use increased in children with different durations of cochlear implant use [68]. Nassar et al. obtained results consistent with these studies in cochlear implant users with SNHL and auditory neuropathy spectrum disorder [70]. BinKhamis et al. reported that electrical artifacts produced by the cochlear implant affect the s-ABR responses and showed that the application of a single-channel approach is feasible for artifact removal [71].

Speech ABR in tinnitus

Omidvar et al. reported that even mild tinnitus affects the temporal aspects of speech stimuli at the subcortical level. In individuals with tinnitus, latency prolongation was observed for all s-ABR waves, but no significant difference was observed in amplitude. There was no significant difference in latency and amplitude in V–A complex measurements, but the slope was significantly reduced. While F_0 amplitude was found to be normal in spectral analysis measurements, a decrease was observed in the coding of F_1 and higher formants. In conclusion, it was found that tinnitus affects the processing of both non-speech and speech stimuli, and s-ABR can provide more information than click ABR. This finding suggests that tinnitus is due to maladaptive plasticity in the central auditory pathways rather than damage to the cochlea alone [72].

Discussion

In studies comparing s-ABR and click ABR measurements; Gonçalves et al. demonstrated that s-ABR has higher sensitivity and specificity than click ABR for identifying phonological disorders [35]. Peixe et al., on the other hand, reported that, unlike the click stimulus, it is not much affected by peripheral hearing loss [54]. These results support studies indicating that speech ABR evaluates regions different from the click stimulus [14, 43].

Similar s-ABR response analysis measures were obtained in studies conducted with children and adults whose native language are English, Brazilian Portuguese, Korean, Arabic, Hebrew, Persian, Portuguese, Greek, and French [12, 16, 17, 19, 24, 27, 32, 35, 37–39, 42, 43, 45, 48, 52, 55, 61, 66, 69, 72]. Only Sanfins et al. reported different responses in native Italian children and adolescents than others [25]. This suggests that native language difference does not greatly affect s-ABR and that the same s-ABR procedure can be used in individuals with different mother tongues.

In auditory processing disorders [12, 29–32], stuttering [37, 38], sensorineural hearing loss [56, 57], history of otitis media [61, 62], autism spectrum disorder [48–51], attention deficit hyperactivity disorder [52, 53], dyslexia [44, 45, 47], language disorders [32–34], phonological disorders [35, 36], learning disorders [39–43], and tinnitus [72] abnormalities were observed in spectral analysis measurements. The apparent abnormalities obtained suggest that s-ABR assessment would be useful in these patient populations.

Decreased wave latencies and increased amplitudes have been observed with the use of hearing aids and cochlear implants [56, 63–65, 67, 68]. These results are consistent with those obtained from other electrophysiological measurements (ABR, MLR, MMN, P3, etc.) [73, 74]. This suggests that s-ABR can be used as an objective test in hearing aid and cochlear implant follow-up evaluations.

Conclusion

Speech ABR is an electrophysiological measurement applicable to all age groups, showing the processing of auditory information in the upper regions of the brainstem. S-ABR, due to its high degree of reliability; It can be used as a biological marker in hearing loss, auditory processing disorders, learning disorders, language and phonological disorders, attention deficit and hyperactivity disorders, dyslexia and autism spectrum disorders. In addition, the result of this review; demonstrated that s-ABR could be included in audiological evaluation in demonstrating auditory rehabilitation efficacy in individuals with hearing aids and cochlear implants.

Appendix 1

See Table 1.

Table 1 Summaries of the reviewed articles

Authors	Study group	Participants	Native language	s-ABR stimulus	Assessments	Results
Rocha et al. (2010) [14]	Normal hearing	50 young adults aged 19–32		40 ms /da/	Speech and pure tone audiometry, tympanometry, SPIN test, Frequency and duration pattern test, click ABR, s-ABR	S-ABR is a sufficient tool to demonstrate brainstem level audio coding. S-ABR wave latency is longer than click ABR wave latency
Sinha and Basavaraj (2010) [15]	Normal hearing	30 young adults aged 18–25		40 ms /da/	Audiometry, tympanometry, AR, s-ABR	All subjects have s-ABR waves and the s-ABR wave V has a longer latency than those reported for the click stimulus
Pinto and Martinelli (2020) [24]	Normal hearing	21 newborns aged 2–38 days	Brazilian Portuguese	40 ms /da/	Hearing screening, TEOAE, click ABR, s-ABR	s-ABR waves with typical morphology can be obtained in newborns
Sanfins et al. (2016) [19]	Normal hearing	40 children and adolescents aged 8–16	Brazilian Portuguese	40 ms /da/	Audiometry, tympanometry, AR, DDT, Frequency pattern test, GIN, SSI test, click-ABR, s-ABR	Similar s-ABR measurements to adults were obtained
Lee and Han (2017) [16]	Normal hearing	30 young adults aged 21–25	Korean	9 Korean syllables	Audiometry, tympanometry, s-ABR	A clear, distinguishable and similar morphology to English stimuli was observed for all syllables
Sanfins et al. (2019) [25]	Normal hearing	24 children and adolescents aged 9–14	Italian	40 ms /da/	Audiometry, tympanometry, AR, DDT, click-ABR, s-ABR	FFR is an electrophysiological procedure that makes it possible to monitor the processing of auditory information in the subcortical region, which can be applied even to very young subjects
Karawani and Banai (2010) [17]	Normal hearing	34 young adults aged 18–28	Arabic and Hebrew	40 ms /da/	Audiometry, click-ABR, s-ABR	Brainstem processing of the /da/ syllable does not differ between English speakers and speakers of Semitic languages, such as Arabic and Hebrew
Hornickel et al. (2012) [20]	Normal hearing	26 children aged 8–13		170 ms /da/	Audiometry, tympanometry, click ABR, WISC-R, WRT, s-ABR in silence and noise 1 year apart	S-ABR is reproducible and consistent over one year of growth in typically developing children

Table 1 (continued)

Authors	Study group	Participants	Native language	s-ABR stimulus	Assessments	Results
Zakaria ve Jalaei (2017) [21]	Normal hearing	17 children aged 5–9 years		40 ms /da/	Audiometry, tympanometry, and s-ABR at 30 dB SL 3 months apart	The s-ABR recorded at low intensity levels (30 dB SL) in healthy children was maintained over a 3-month period
Song et al. (2011) [18]	Normal hearing	31 young adults aged 19–31, 45 adults aged 19–36		170 ms /da/, /40/ ms da	Audiometry, click ABR, WISC-R, Nonverbal Intelligence Test-3 and s-ABR in silence and noise	S-ABR exhibits a high degree of repeatability in optimal and challenging listening conditions
Rana and Barman (2011) [23]	Normal hearing	35 young adults aged 18–23		40 ms /da/	Audiometry, tympanometry, AR, SPIN, TEOAE, s-ABR	There is a significant relationship between the S-ABR wave V latency and the TEAOE
Dhar et al. (2009) [22]	Normal hearing	28 young adults aged 19–30		40 ms /da/	Audiometry, click ABR, DPOAE, s-ABR	Certain aspects of S-ABR are associated with DPOAE
Vander Werf and Burns (2011) [26]	Normal hearing	19 young adults aged 20–26 and 18 older aged 61–78		40 ms /da/	Audiometry, click ABR, s-ABR	S-ABR can provide information about the ability of the aging auditory system to encode temporal cues
Lotfi et al. (2019) [27]	Normal hearing	18 young adults aged 18–25	Persian	40 ms /da/	Audiometry, tympanometry, AR, TEOAE, suppression OAE, SPIN, dichotic listening and lateralization tests in noise, click ABR, s-ABR in silence and noise	In contralateral noise, s-ABR can be used to evaluate the rostral part of the auditory efferent system
Moossavi et al. (2020) [28]	Normal hearing	14 young adults aged 18–25		40 ms /da/	Audiometry, tympanometry, lateralization tests, s-ABR in silent and three different SNR conditions	S-ABR demonstrates auditory afferent and efferent system cooperation to process complex auditory stimuli in noise

Table 1 (continued)

Authors	Study group	Participants	Native language	s-ABR stimulus	Assessments	Results
Rocha-Muniz et al. (2016) [30]	CAPD	27 children aged 7–15		40 ms /da/	Audiometry, s-ABR, auditory localization, Verbal and Non-verbal Sequential Memory, SPIN, SSW Frequency and Duration Pattern tests, GIN	Abnormal s-ABR has generally been found to represent auditory processing disorders, suggesting that it can be used in clinical practice as an adjunct tool in the evaluation of APD. It can also provide information about speech sound perception in children whose behavioral assessment is difficult
Rocha-Muniz et al. (2014) [12]	CAPD and language disorder	75 children aged 6–12 years (25 TD, 25 APD, 25 LD)	Brazilian Portuguese	40 ms /da/	Audiometry, tympanometry, DDT, SSW, SPIN, Frequency pattern test, ABFW Child Language Test, TELD-3, RAVEN test, s-ABR	The S-ABR can be used clinically for the assessment of central hearing function and can also provide additional information in the diagnosis of language impairment and APD
Kumar and Singh (2015) [31]	CAPD	30 children aged 8–12 years (15 APD, 15 TD)		40 ms /da/	Audiometry, SCAP, ERS, click ABR, s-ABR	The S-ABR BioMARK protocol can clearly distinguish between children at risk for (C)APD and typically developing children
Rocha-Muniz et al. (2012) [32]	CAPD and language disorder	57 children aged 6–12 (18 TD, 18 APD, 21 LD)	Brazilian Portuguese	40 ms /da/	Pure tone and speech audiometry, tympanometry, AR, DDT, SSW, SPIN, Frequency pattern test, ABFW Child Language Test, TELD-3, RAVEN, s-ABR	S-ABR results differ among children with auditory processing and speech-language disorders of neural processes in the auditory brainstem
Flippini and Schochat (2009)	CAPD	40 participants between the ages of 7–24 (20 APD, 20 TD)		40 ms /da/	Audiometry, click-ABR, s-ABR	S-ABR is a valid method for evaluating brainstem auditory function in individuals with auditory processing disorder

Table 1 (continued)

Authors	Study group	Participants	Native language	s-ABR stimulus	Assessments	Results
Gabr and Darwish (2016) [34]	Language disorders	40 children aged 3–7 (20 LD, 20 Normal)		206 ms /da/	Pure tone and speech audiometry, tympanometry, AR, PLS-4, click and s-ABR	S-ABR is a highly efficient, easy, fast, reliable and well-tolerated procedure that allows for early diagnosis and management of language processing problems
Flippini et al. (2012)	CAPD and language disorders	30 children aged 7–13 years (9 APD, 7 Normal, 6 children AR + ST, 8 children only ST)		40 ms /da/	Audiometry, tympanometry, click ABR, RAVEN, SPIN, SSW, DDT, s-ABR	The effectiveness of formal auditory training can be demonstrated with s-ABR in background noise
Gonçalves et al. (2011) [35]	Phonological Disorder	36 children aged 7–11 (18 PD, 18 TD)	Portuguese	40 ms /da/	Audiometry, tympanometry, AR, ABFW Child Language Test, click ABR, s-ABR	Abnormal s-ABR findings may be a biological marker of phonological disorders. However, these results cannot identify the biological origins of phonological problems
ElBeltagy et al. (2019)	Phonological Disorder	30 children aged 3.5–5.5 (15 PD, 15 TD)		/ba/	Pure tone and speech audiometry, tympanometry, AR, AAT, click ABR, s-ABR, MMN	In children with phonological disorders, cortical auditory processing can be evaluated with s-ABR and MMN
Wible et al. (2005) [39]	Learning Disorders	20 children with a mean age of 11 (11 LD, 9 TG)	English	40 ms /da/	Audiometry, SCI, auditory-perceptual tests, s-ABR and s-cortical responses	Weakened correlations between the brainstem and auditory cortex have been found in children with language-based learning disabilities
Ghannoum et al. (2014) [40]	Learning Disorders	60 children aged 6–8, 8–10, 10–12 (30 LD, 30 TD)		40 ms /da/	Pure tone and speech audiometry, tympanometry, AR, ADT, Stanford-Binet Intelligence Scale, s-ABR	For children with learning disabilities, it has been recommended to routinely perform the s-ABR test in addition to behavioral auditory processing tests
Sachin et al. (2019) [41]	Learning Disorders	25 children aged 5–12 years		40 ms /da/	Pure tone and speech audiometry, tympanometry, AR, click ABR and s-ABR	The S-ABR is an effective tool to identify underlying auditory processing difficulties in children with learning disabilities and may be helpful in early intervention

Table 1 (continued)

Authors	Study group	Participants	Native language	s-ABR stimulus	Assessments	Results
Malayeri et al. (2014) [42]	Learning Disorders	83 children aged 8–12 (49 LD, 34 TD)	Persian	40 ms /da/	Audiometry, tympanometry, WISC, WIAT-II, click ABR, s-ABR	A significant delay in the temporal components of both click and speech ABR has been observed in children with learning disabilities
Song et al. (2006) [43]	Learning Disorders	234 children aged 8–12 (119 LD, 115 TD)	English	40 ms /da/	Woodcock-Johnson psychoeducational tests, click ABR and s-ABR	Click and s-ABR largely reflect separate neural processes, and only the processes involved in encoding complex signals such as speech are impaired in children with learning disabilities
Kouni et al. (2013) [45]	Dyslexia and other LD	40 young adults aged 18–23 (10 dyslexia, 10 other LD, 20 TD)	Greek	/baba/	WAIS-IV, Pure tone and speech audiometry, tympanometry, AR, click ABR, s-ABR	Subjects with dyslexia or other learning disabilities have longer A and C wave latency. Elongation is higher in those with dyslexia
Kouni et al. (2006) [46]	Dyslexia	20 young adults aged 18–23 (10 Dyslexia, 10 Normal)		/ma/	Pure tone and speech audiometry, tympanometry, click ABR, s-ABR	S-ABR baseline responses were prolonged in young adults with dyslexia compared to the control group
Billiet and Bellis (2011) [44]	Dyslexia	32 children aged 8–12 (10 abnormal brainstem timing, 20 normal)		40 ms /da/	Audiometry, tympanometry, click ABR, s-ABR, DDT, Frequency pattern test, CS, LPFS	Through behavioral tools of central auditory assessment, BioMARK can identify a subset of children who will not meet diagnostic criteria for (C) APD but who may benefit from auditory-based intervention approaches
Hornickel and Kraus (2013) [47]	Dyslexia	100 children aged 6–13		170 ms /ba/ ve /ga/	Audiometry, click ABR, Spoken Word Reading Activity: Vision subtest, ADHD RS- IV, s-ABR	Poor readers have more variable s-ABR responses than average and good readers
Ramezani et al. (2019) [48]	ASD	56 children with an average age of 14	Farsça	40 ms /da/	Pure tone and speech audiometry, tympanometry, DSM-IV, s-ABR	It was concluded that children with ASD have deficiencies in the temporal nerve encoding of speech at the brainstem level

Table 1 (continued)

Authors	Study group	Participants	Native language	s-ABR stimulus	Assessments	Results
Kamita et al. (2020) [49]	ASD	30 children aged 7–12 (15 OSD, 15 TD)		40 ms /da/	Pure tone and speech audiometry, tympanometry, AR, DSM-IV, ABC, Wisconsin Card Mapping Test, click ABR and s-ABR	In children with autism, the initial portion of the verbal stimulus may have faster neural encoding, suggesting hypersensitivity to complex sounds, such as speech
Russo et al. (2009) [50]	ASD	39 children aged 7–13 (21 ASD, 18 TD)		40 ms /da/	Audiometry, click ABR, WASI, CELF, s-ABR in silence and noise	S-ABR may be a clinical tool to evaluate auditory processing and to observe the effects of auditory training in the ASD population
Chen et al. (2019) [51]	ASD	35 children aged 3–6 (15 ASD, 20 TD)		40 ms /da/	Audiometry, GDDS, CARS, ADOS, s-ABR	S-ABR can be used as an objective measure in evaluating the language performance of children with ASD
Azzam and Hasan (2010) [52]	ADHD/**C**	30 children aged 5–10 years (15 ADHD, 15 TD)	Arabic	40 ms /da/	Audiometry, tympanometry, WISC-R, MINI-Kid, click ABR, s-ABR, MMN	S-ABR may serve as a biomarker for neural asynchrony in the brainstem in children with ADHD
Jafari et al. (2015) [53]	ADHD	84 children aged 8–12 (50 ADHD, 34 TD)		40 ms /da/	Audiometry, tympanometry, AR, WISC-R, DSM-IV, click ABR, s-ABR	Children with ADHD have a common dysfunction in the processing of non-speech and speech stimuli at the brainstem level
Tahaei et al. (2014) [37]	Stuttering	50 adults aged 16–35 (25 PDS, 25 TD)	Persian	40 ms /da/	Audiometry, tympanometry, SSI-3, click ABR, s-ABR	Neural coding deficiencies for temporal features have been observed in adults with PDS in the early stages of the auditory pathway
Crivellaro Gonçalves et al. (2015) [38]	Stuttering	20 children aged 7–11 (10 stutterers, 10 TD)	Brazilian Portuguese	40 ms /da/	Audiometry, tympanometry, SSI-3, click ABR and s-ABR	Compared with typically developing children, there are differences in the neural processes involved in processing acoustic information in children who stutter

Table 1 (continued)

Authors	Study group	Participants	Native language	s-ABR stimulus	Assessments	Results
Koravand et al. (2017) [55]	Mild to moderate SNHL	25 children aged 6–14 (12 SNHL, 13 normal hearing)	French and English	40 ms /da/	Audiometry, tympanometry, click ABR, s-ABR	Measuring s-ABR responses as subcortical markers in children with hearing loss may provide an objective measure to evaluate the function of the central auditory system
Nada et al. (2016) [58]	Mild to moderate SNHL	60 adults aged 18–50 (40 mild to moderate SNHL, 20 normal hearing)		114 ms /ba/, 206 ms /da/	Pure tone and speech audiometry, tympanometry, AR, click ABR, s-ABR	Speech processing is affected at the brainstem level in people with mild to moderate SNHL
Jalaeia and Zakariab (2019) [57]	Moderate SNHL	32 children aged 4–9 (17 SNHL, 15 normal hearing)		40 ms /da/	Audiometry, tympanometry, OAE, click ABR, s-ABR	In children with moderate SNHL, the brainstem coding of the temporal and phoneme transitional parts of the speech syllable is significantly impaired
Peixe et al. (2018) [54]	Moderate SNHL	11 Adults with SNHL aged 18–59		40 ms /da/	Audiometry, tympanometry, click ABR, s-ABR	Unlike click stimulus, S-ABR is not affected by peripheral hearing loss and can be performed in people with moderate SNHL
Anderson et al. (2013) [60]	Mild to moderate SNHL	30 older adults aged 60–71 (15 mild to moderate hearing loss, 15 normal hearing)		40 ms /da/	Audiometry, tympanometry, WASI, click ABR, s-ABR	There is some deterioration in the envelope to fine structure balance in the hearing loss group compared to the normal hearing group
Abd El-Ghaffar et al. (2017) [59]	Unilateral hearing loss	45 adults aged 21–46 (30 UHL, 15 normal hearing		40 ms /da/	Audiometry, tympanometry, AR, s-ABR in silence and ipsilateral noise	Deficiencies in encoding rapidly changing temporal cues at the brainstem level affect the ability to understand rapid speech or speak separately from background noise in adults with UHL

Table 1 (continued)

Authors	Study group	Participants	Native language	s-ABR stimulus	Assessments	Results
Sanfins et al. (2017) [61]	Otitis media	60 children aged 8–14 years (30 OM, 30 Normal)	Brazilian Portuguese	40 ms /da/	Audiometry, tympanometry, AR, click ABR, s-ABR	Children with SOM in their first 6 years of life and who underwent myringotomy for bilateral ventilation tube placement show changes in their s-ABR response
El-Kabarity et al. (2015) [62]	Otitis media with effusion	55 children aged 5–11 years (25 long-term OME, 30 new-onset OME		40 ms /da/	Audiometry, tympanometry, AR, click ABR, s-ABR	Prolonged OME in children is associated with inadequate neural timing in response to the onset and stabilization of transient speech stimuli and causes a mild impairment of speech coding in the brainstem
Bellier et al. (2015) [66]	HA stimulation	4 normal hearing adults aged 22–25	French	180 ms /ba/	Audiometry, tympanometry, AR, click ABR, s-ABR	Through hearing aid stimulation, s-ABR ensures high-quality responses and works as well as insert headphones for the same level of stimulation
Leite et al. (2018) [56]	HA user	32 children aged 7–12 years (18 bil. mild to moderate SNHL, 14 normal hearing)		40 ms /da/	Audiometry, tympanometry, s-ABR	Hearing aid use has been shown to increase neural plasticity of the central auditory nervous system after a long period of sensory stimulation
BinKhamis et al. (2019a) [63]	HA user	98 hearing aid users aged 18–60 years		40 ms /da/	Audiometry, tympanometry, AR, DST, SIN, s-ABR	S-ABR has the potential for clinical application as an objective measure of speech perception with hearing aids
Shetty et al. (2017) [64]	HA user	60 hearing aid users with moderate SNHL aged 15–65 years		94 ms /da/, 301 ms /si/	Pure tone and speech audiometry, tympanometry, AR, click ABR, aided and non-aided s-ABR	Although hearing aid spectra are nearly identical between good hearing aid users and poor hearing aid users, subtle physiological variations exist in the auditory brainstem

Table 1 (continued)

Authors	Study group	Participants	Native language	s-ABR stimulus	Assessments	Results
Hassaan et al. (2016) [65]	HA user	40 HA user with moderate-to-severe SNHL aged 18–40 years		114 ms /ba/, 213 ms /ga/, 206 ms /da/	Audiometry, tympanometry, TEN test, s-ABR	The brainstem can encode speech signals with stimuli with spectral maxima perpendicular to the cochlear dead regions in long-term hearing aid users. This can be explained by the neuroplasticity of the auditory system after prolonged use of the hearing aid
Gabr and Hassaan (2015) [67]	CI user	20 children aged 2 -6 years		206 ms /da/	Aided pediatric audiometry, tympanometry, OAE, CT, MRI, click ABR, s-ABR	Speech processing in children with CI can be evaluated efficiently at both the brainstem and cortical levels early after implantation. S-ABR can be routinely used in postoperative evaluation in CI programs
BinKhamis et al. (2019b) [71]	CI user	12 adults CI users aged 39–60 years		40 ms /da/	s-ABR	Demonstrates potential for implementation of a single-channel approach to artifact removal.
Jarollahi et al. (2020) [69]	CI user	40 children aged 8–10 years (20 right ear CI, 20 normal hearing)	Farsça	40 ms /da/	Audiometry, telemetry, s-ABR	Free-field recorded s-ABR is useful for assessing speech processing at the brainstem level in CI users as an objective, non-invasive and efficient clinical procedure
Rahman et al. (2017) [68]	CI user	31 children aged 4–5 years (10 children for 1 year, 12 for 2 years, 9 children for 3 years using CI)		40 ms /da/	Pure tone and speech audiometry CI fitting, ADT, WIN, MMN, s-ABR	Children using CI show cortical and brainstem activation from the first year and these activity changes improve with CI use. MMN and s-ABR can be early and critical target indicators of optimum speech coding after programming the CI

Table 1 (continued)

Authors	Study group	Participants	Native language	s-ABR stimulus	Assessments	Results
Nassar et al. (2020)	CI user	45 participants aged 2.9–29 years (29 CI users; 16 SNHL, 13 ANSD, 16 normal hearing)		150 ms /da/	Pure tone and speech audiometry, tympanometry, psychosocial assessment, APHAB, s-cortical evoked responses, s-ABR	S-ABR responses can be successfully recorded in individuals with a cochlear implanted auditory neuropathy spectrum disorder
Omidvar et al. (2018) [72]	Tinnitus	38 adults with an average age of 35 (18 Tinnitus, 20 Normal)	Persian	40 ms /da/	Audiometry, tympanometry, CT, MRI, THI, Tinnitus frequency and intensity assessment, click ABR, s-ABR	It has been found that tinnitus affects the processing of both non-speech and speech stimuli, and s-ABR can provide more information than click ABR

PTA pure tone average, *SPIN* speech perception in noise, *AR* acoustic reflexes, *NHS* newborn hearing screening, *TEOAE* transient otoacoustic emissions, *DDT* dichotic digit test, *GIN* gap in noise, *SSI* synthetic sentence identification test, *WRT* word reading test, *WISCH-R* Weschler Intelligence Scale for Children, *DPOAE* Distortion Product OAE, *SNR* signal to noise ratio, *APD* auditory processing disorder, *SSW* staggered Spondaic Word test, *LD* language disorders, *TD* typically developed, *TELD-3* test of early language development-3, *RAVEN* Raven's colored progressive matrices, *SCAP* screening checklist for auditory processing, *ERS* early reading skills, *PLS-4* Preschool Language Scales-4, *AR* auditory rehabilitation, *ST* speech therapy, *PD* phonological disorders, *AAT* Arabic articulation test, *MMN* mismatch negativity, *SCI* short cognitive index, *ALT* Arabic Language Test, *WIAT-II* Wechsler Individual Achievement Test-II, *WAIS-IV* Wechsler Adult Intelligence Scale-IV, *CS* competing sentences test, *LPFS* low-pass filter speech test, *ADHD RS-IV* ADHD Rating Scale-IV, *ASD* autism spectrum disorder, *DSM-IV* diagnostic and statistical manual of mental disorders IV, *ABC* autism behavior checklist, *WASI* Wechsler Abbreviated Scale of Intelligence, *CELF* clinical evaluation of language fundamentals, *GDDS* Gesell Developmental Schedules, *CARS* Childhood Autism Rating Scale, *ADOS* autism diagnostic observation schedule, *ADHD* attention deficit hyperactivity disorder, *MINI-Kid* International Neuropsychiatric Interview for Children and Adolescents, *PDS* persistent developmental stuttering, *SSI-3* Stuttering Severity Instrument-3, *SNHL* sensorineural hearing loss, *OAE* otoacoustic emissions, *HL* hearing loss, *UHL* unilateral hearing loss, *OME* otitis media with effusion, *HA* hearing aid, *DST* Digit Span Test, *SIN* speech in noise test, *CT* computer tomography, *MRI* magnetic resonance imaging, *CI* cochlear implant, *WIN* word in noise test, *APHAB* abbreviated profile of hearing aid benefit, *ANSD* auditory neuropathy spectrum disorder, *THI* tinnitus handicap inventory

Acknowledgements Not applicable.

Author contributions All authors read and approved the final manuscript. MBB; acquisition and analysis of data, drafting and reviewing of the manuscript. NG; acquisition and analysis of data. EK; drafting and reviewing of the manuscript. NB; conception and design of the study. OGT; conception and design of the study.

Funding There are no financial resources.

Availability of data and materials Not applicable.

Declarations

Conflict of interest The authors declare that they have no competing interests.

Ethics approval and consent to participate Not applicable.

Consent for publication Yes.

References

1. Johnson KL, ve Nicol TG, Kraus N (2005) Brain stem response to speech: a biological marker of auditory processing. Ear Hear 26(5):424–434
2. Banai K, Hornickel J, Skoe E, Nicol T, Zecker S, Kraus N (2009) Reading and subcortical auditory function. Cereb Cortex 19(11):2699–2707
3. Skoe E, Kraus N (2010) Auditory brainstem response to complex sounds: a tutorial. Ear Hear 31(3):302–324
4. Hornickel J, Skoe E, Kraus N (2009) Subcortical laterality of speech encoding. Audiol Neurotol 14(3):198–207
5. Sanfins MD, Hatzopoulos S, Donadon C, Diniz TA, Borges LR, Skarzynski PH, Francisca Colella-Santos M (2018) An analysis of the parameters used in speech ABR assessment protocols. J Int Adv Otol 14(1):100–105
6. Sanfins MD, Skarzynski PH, Colella-Santos M (2017) Speech-evoked brainstem response. In: Hatzopoulos S (ed) Advances in clinical audiology. InTech, London, pp 9–28
7. Chandrasekaran B, Kraus N (2010) The scalp-recorded brainstem response to speech: neural origins and plasticity. Psychophysiology 47(2):236–246
8. Banai K, Abrams D, Kraus N (2007) Sensory-based learning disability: insights from brainstem processing of speech sounds. Int J Audiol 46(9):524–532
9. Abrams D, Kraus N (2015) Auditory pathway representations of speech sounds in humans. In: Katz J, Chasin M, English K, Hood L, Tillery K (eds) Handbook of clinical audiology. Wolters Kluwer Health, Philadelphia, pp 527–544
10. Johnson KL, Nicol TG, Zecker SG, Kraus N (2007) Auditory brainstem correlates of perceptual timing deficits. J Cognit Neurosci 19(3):376–385
11. Johnson KL, Nicol T, Zecker SG, Krause N (2008) Developmental plasticity in the human auditory brainstem. J Neurosci 28(15):4000–4007
12. Rocha-Muniz CN, Befi-Lopes DM, Schochat E (2014) Sensitivity, specificity and efficiency of speech-evoked ABR. Hear Res 317:15–22
13. Sanfins MD, Borges LR, Ubiali T, Colella-Santos MF (2017) Speech-evoked auditory brainstem response in the differential diagnosis of scholastic difficulties. Braz J Otorhinolaryngol 83(1):112–116
14. Rocha CN, Filippini R, Moreira RR, Neves IF, Schochat E (2010) Brainstem auditory evoked potential with speech stimulus. Pro-fono revista de atualizacao cientifica 22(4):479–484
15. Sinha SK, Basavaraj V (2010) Speech evoked auditory brainstem responses: a new tool to study brainstem encoding of speech sounds. Indian J Otolaryngol Head Neck Surg 62(4):395–399
16. Lee J, Han W (2017) Auditory brainstem encoding of plosives in Korean normal hearing listeners. Audiol Speech Res 13(2):101–107
17. Karawani H, Banai K (2010) Speech-evoked brainstem responses in Arabic and Hebrew speakers. Int J Audiol 49(11):844–849
18. Song JH, Nicol T, Kraus N (2011) Test–retest reliability of the speech-evoked auditory brainstem response. Clin Neurophysiol 122(2):346–355
19. Sanfins MD, Borges LR, Ubiali T, Donadon C, Diniz Hein TA, Hatzopoulos S, Colella-Santos MF (2016) Speech-evoked brainstem response in normal adolescent and children speakers of Brazilian Portuguese. Int J Pediatric Otorhinolaryngol 90:12–19
20. Hornickel J, Knowles E, Kraus N (2012) Test-retest consistency of speech-evoked auditory brainstem responses in typically-developing children. Hear Res 284(1–2):52–58
21. Zakaria MN, Jalaei B (2017) Test-retest reliability of speech-evoked auditory brainstem response in healthy children at a low sensation level. Int J Pediatric Otorhinolaryngol 102:28–31
22. Dhar S, Abel R, Hornickel J, Nicol T, Skoe E, Zhao W, Kraus N (2009) Exploring the relationship between physiological measures of cochlear and brainstem function. Clin Neurophysiol 120(5):959–966
23. Rana B, Barman A (2011) Correlation between speech-evoked auditory brainstem responses and transient evoked otoacoustic emissions. J Laryngol Otol 125(9):911–916
24. Pinto E, Martinelli MC (2020) Brainstem auditory evoked potentials with speech stimulus in neonates. Braz J Otorhinolaryngol 86(2):191–200
25. Sanfins MD, Hatzopoulos S, Hein TAD, Bordin T, Skarzynski PH, Colella-Santos MF (2019) Evaluation of the frequency following response in Italian children: a pilot study. J Hear Sci 9(2):45–50
26. Vander Werff KR, Burns KS (2011) Brain stem responses to speech in younger and older adults. Ear Hear 32(2):168–180
27. Lotfi Y, Moossavi A, Javanbakht M, Faghih Zadeh S (2019) Speech-ABR in contralateral noise: a potential tool to evaluate rostral part of the auditory efferent system. Med Hypotheses 132:109355
28. Moossavi A, Lotfi Y, Javanbakht M, Faghihzadeh S (2020) Speech-evoked auditory brainstem response; electrophysiological evidence of upper brainstem facilitative role on sound lateralization in noise. Neurol Sci 41(3):611–617
29. Filippini R, Schochat E (2009) Brainstem evoked auditory potentials with speech stimulus in the auditory processing disorder. Braz J Otorhinolaryngol 75(3):449–455
30. Rocha-Muniz CN, Filippini R, Neves-Lobo IF, Rabelo CM, Morais AA, Murphy CF, Calarga KS, Leite LC, Pires MM, Sena-Yoshinaga TA, Schochat E (2016) Can speech-evoked Auditory Brainstem Response become a useful tool in clinical practice? CoDAS 28(1):77–80
31. Kumar P, Singh NK (2015) BioMARK as electrophysiological tool for assessing children at risk for (central)

auditory processing disorders without reading deficits. Hear Res 324:54–58
32. Rocha-Muniz CN, Befi-Lopes DM, Schochat E (2012) Investigation of auditory processing disorder and language impairment using the speech-evoked auditory brainstem response. Hear Res 294(1–2):143–152
33. Filippini R, Befi-Lopes DM, Schochat E (2012) Efficacy of auditory training using the auditory brainstem response to complex sounds: auditory processing disorder and specific language impairment. Folia Phoniatr Logop 64(5):217–226
34. Gabr TA, Darwish ME (2016) Speech auditory brainstem response audiometry in children with specific language impairment. Hear Balance Commun 14(1):50–58
35. Gonçalves IC, Wertzner HF, Samelli AG, Matas CG (2011) Speech and non-speech processing in children with phonological disorders: an electrophysiological study. Clinics 66(2):293–298
36. El-Beltagy R, Galhom D, Hassan EHM (2019) Auditory brainstem response and speech mismatch negativity in children with phonological disorders. Egypt J Otolaryngol 35(1):79–85
37. Tahaei AA, Ashayeri H, Pourbakht A, Kamali M (2014) Speech evoked auditory brainstem response in stuttering. Scientifica 2014:1–7
38. Crivellaro Goncalves I, Furquim de Andrade CR, Gentile Matas C (2015) Auditory processing of speech and non-speech stimuli in children who stutter: electrophysiological evidences. Brain Disord Therapy 4(5):1–5
39. Wible B, Nicol T, Kraus N (2005) Correlation between brainstem and cortical auditory processes in normal and language-impaired children. Brain J Neurol 128(2):417–423
40. Ghannoum MT, Shalaby AA, Dabbous AO, Abd-El-Raouf ER, Abd-El-Hady HS (2014) Speech evoked auditory brainstem response in learning disabled children. Hear Balance Commun 12(3):126–142
41. Sachin MS, Kohli A, Panda N, Arya S (2019) Speech evoked auditory brainstem responses in children with learning disability. Int J Otorhinolaryngol Head Neck Surg 5(1):101–105
42. Malayeri S, Lotfi Y, Moossavi SA, Rostami R, Faghihzadeh S (2014) Brainstem response to speech and non-speech stimuli in children with learning problems. Hear Res 313:75–82
43. Song JH, Banai K, Russo NM, Kraus N (2006) On the relationship between speech- and nonspeech-evoked auditory brainstem responses. Audiol Neuro-otol 11(4):233–241
44. Billiet CR, Bellis TJ (2011) The relationship between brainstem temporal processing and performance on tests of central auditory function in children with reading disorders. J Speech Lang Hear Res 54(1):228–242
45. Kouni SN, Giannopoulos S, Ziavra N, Koutsojannis C (2013) Brainstem auditory evoked potentials with the use of acoustic clicks and complex verbal sounds in young adults with learning disabilities. Am J Otolaryngol 34(6):646–651
46. Kouni SN, Papadeas ES, Varakis IN, Kouvelas HD, Koutsojannis CM (2006) Auditory brainstem responses in dyslexia: comparison between acoustic click and verbal stimulus events. J Otolaryngol 35(5):305–309
47. Hornickel J, Kraus N (2013) Unstable representation of sound: a biological marker of dyslexia. J Neurosci 33(8):3500–3504
48. Ramezani M, Lotfi Y, Moossavi A, Bakhshi E (2019) Auditory brainstem response to speech in children with high functional autism spectrum disorder. Neurol Sci 40(1):121–125
49. Kamita MK, Silva L, Magliaro F, Kawai R, Fernandes F, Matas CG (2020) Brainstem auditory evoked potentials in children with autism spectrum disorder. J Pediatr (Rio J) 96(3):386–392
50. Russo N, Nicol T, Trommer B, Zecker S, Kraus N (2009) Brainstem transcription of speech is disrupted in children with autism spectrum disorders. Dev Sci 12(4):557–567
51. Chen J, Liang C, Wei Z, Cui Z, Kong X, Dong CJ et al (2019) Atypical longitudinal development of speech-evoked auditory brainstem response in preschool children with autism spectrum disorders. Autism Res 12(7):1022–1031
52. Azzam H, Hassan DM (2010) Speech-evoked auditory potentials in attention deficit hyperactivity disorder. Audiol Med 8(3):129–136
53. Jafari Z, Malayeri S, Rostami R (2015) Subcortical encoding of speech cues in children with attention deficit hyperactivity disorder. Clin Neurophysiol 126(2):325–332
54. Peixe BP, Silva D, Biaggio E, Bruno RS, Sanguebuche TR, Garcia MV (2018) Applicability of evoked auditory brainstem responses with complex stimuli in adults with hearing loss. Int Arch Otorhinolaryngol 22(3):239–244
55. Koravand A, Al Osman R, Rivest V, Poulin C (2017) Speech-evoked auditory brainstem responses in children with hearing loss. Int J Pediatric Otorhinolaryngol 99:24–29
56. Leite RA, Magliaro FC, Raimundo JC, Gândara M, Garbi S, Bento RF et al (2018) Effect of hearing aids use on speech stimulus decoding through speech-evoked ABR. Braz J Otorhinolaryngol 84(1):66–73
57. Jalaeia B, Zakariab MN (2019) Speech-evoked auditory brainstem response in children with sensorineural hearing loss. Glob J Otolaryngol 20(4):71–80
58. Nada NM, Kolkaila EA, Gabr TA, El-Mahallawi TH (2016) Speech auditory brainstem response audiometry in adults with sensorineural hearing loss. Egypt J Ear Nose Throat Allied Sci 17(2):87–94
59. Abd El-Ghaffar NM, El-Gharib AM, Kolkaila EA, Elmahallawy TH (2018) Speech-evoked auditory brainstem response with ipsilateral noise in adults with unilateral hearing loss. Acta otolaryngol 138(2):145–152
60. Anderson S, Parbery-Clark A, White-Schwoch T, Drehobl S, Kraus N (2013) Effects of hearing loss on the subcortical representation of speech cues. J Acoust Soc Am 133(5):3030–3038
61. Sanfins MD, Borges LR, Donadon C, Hatzopoulos S, Skarzynski PH, Colella-Santos MF (2017) Electrophysiological responses to speech stimuli in children with otitis media. J Hear Sci 7(4):9–19
62. El-Kabarity RH, Abdel Rahman TT, Abdel Kader HA, Sanyelbhaa H (2015) Effect of otitis media with effusion on brainstem timing in children. Hear Balance Commun 14(1):20–24
63. BinKhamis G, Forte AE, Reichenbach T, O'Driscoll M, Kluk K (2019) Speech auditory brainstem responses in adult hearing aid users: effects of aiding and background noise, and prediction of behavioral measures. Trends Hear 23:1–20
64. Shetty HN, Puttabasappa M (2017) Encoding of speech sounds at auditory brainstem level in good and poor hearing aid performers. Braz J Otorhinolaryngol 83(5):512–522
65. Hassaan MR, Ibraheem OA, Galhom DH (2016) Brainstem encoding of aided speech in hearing aid users with cochlear dead region(s). Int Arch Otorhinolaryngol 20(3):226–234
66. Bellier L, Veuillet E, Vesson JF, Bouchet P, Caclin A, Thai-Van H (2015) Speech Auditory Brainstem Response through hearing aid stimulation. Hear Res 325:49–54
67. Gabr TA, Hassaan MR (2015) Speech processing in children with cochlear implant. Int J Pediatric Otorhinolaryngol 79(12):2028–2034
68. Rahman TTA, Nada IM, Kader HAAA, Monem AAA (2017) Neural representation of speech in pediatric cochlear implant recipients. Egypt J Otolaryngol 33:535–545
69. Jarollahi F, Valadbeigi A, Jalaei B, Maarefvand M, Zarandy MM, Haghani H et al (2020) Sound-field speech evoked auditory brainstem response in cochlear-implant recipients. J Audiol Otol 24(2):71–78
70. Nassar AAM, Hassan DM, Younis A, Abdel Rahman TT (2020) Speech evoked potentials in cochlear implant recipients with

auditory neuropathy spectrum disorder. Hear Balance Commun 1–11
71. BinKhamis G, Perugia E, O'Driscoll M, Kluk K (2019) Speech-ABRs in cochlear implant recipients: feasibility study. Int J Audiol 58(10):678–684
72. Omidvar S, Mahmoudian S, Khabazkhoob M, Ahadi M, Jafari Z (2018) Tinnitus impacts on speech and non-speech stimuli. Otol Neurotol 39(10):921–928
73. Kelly A, Purdy S (2016) Change in speech perception and auditory evoked potentials over time after unilateral cochlear implantation in postlingually deaf adults. Semin Hear 37(1):62–73
74. Kolkaila EA, Emara AA, Gabr TA (2012) Cortical auditory evoked potentials in children using hearing aids. Audiol Med 10(3):132–142