AUDITORY SKILLS IN SCHOOLCHILDREN AND THEIR IMPACT ON LEARNING

COMPETÊNCIAS AUDITIVAS EM ESCOLARES E SEU IMPACTO NA APRENDIZAGEM

HABILIDADES AUDITIVAS EN ESCOLARES Y SU IMPACTO EN EL APRENDIZAJE

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ABSTRACT

Considering the importance of evaluating auditory interventions to improve learning, the objective was to investigate the efficacy of two therapeutic procedures, Acoustically Controlled Auditory Training (ACAT) and the NeuroAuditory Stimulation System (NASS), analyzed individually and in combination, to verify the influence of the order of application on the effects of stimulation. To this end, 30 children aged 8 to 11 years, equally distributed by sex and age, were assessed using pure-tone audiometry, behavioral auditory processing tests (dichotic listening TDD, monotic listening PSI, temporal resolution GIN, and temporal ordering TPD), short (FFR) and long-latency auditory evoked potentials (P300), as well as the Visual Perception Assessment (DTVP-2) and the SAB Scale, before and after the interventions. Thus, it was observed that, in the isolated intervention, ACAT was effective in the electrophysiological procedures (FFR and P300), in the behavioral auditory tests (PSI and TPD) and in the SAB Scale;. At the same time, NASS showed a positive effect on FFR, the PSI test and item 4 of the SAB Scale. The combined interventions showed greater efficacy, especially when ACAT was applied before NASS, suggesting that NASS potentiates the effects of ACAT. This allowed us to conclude that the combined use of both protocols constitutes a promising approach for auditory and cognitive rehabilitation, by promoting behavioral and neurophysiological advances, and broadening the understanding of neural plasticity mechanisms and their implications for the learning process.

Keywords: Auditory Evoked Potentials. Spatial Processing. Auditory Perception. Acoustic Stimulation. Rehabilitation.

RESUMO

Considerando a importância de avaliar intervenções auditivas para a melhoria da aprendizagem, objetivou-se investigar a eficácia de dois procedimentos terapêuticos, o Treinamento Auditivo Acusticamente Controlado (TAAC) e o Sistema de Estimulação NeuroAuditiva (SENA), analisados individualmente e combinados, a fim de verificar a influência da ordem de aplicação sobre os efeitos da estimulação. Para tanto, procedeu-se à avaliação de 30 crianças de 8 a 11 anos, igualmente distribuídas por sexo e idade, por meio de audiometria tonal, testes comportamentais de processamento auditivo (escuta dicótica TDD, escuta monótica PSI, resolução temporal GIN e ordenação temporal TPD),

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potenciais evocados auditivos de curta (FFR) e longa latência (P300), além da Avaliação da Percepção Visual (DTVP-2) e da Escala SAB, antes e após as intervenções. Desse modo, observou-se que, na intervenção isolada, o TAAC foi eficaz nos procedimentos eletrofisiológicos (FFR e P300), nos testes comportamentais auditivos (PSI e TPD) e na Escala SAB; enquanto o SENA apresentou efeito positivo no FFR, no teste PSI e no item 4 da Escala SAB. As intervenções combinadas evidenciaram maior eficácia, especialmente quando o TAAC foi aplicado antes do SENA, sugerindo que o SENA potencializa os efeitos do TAAC. Foi possível concluir que o uso combinado de ambos os protocolos constitui uma abordagem promissora para a reabilitação auditiva e cognitiva, ao promover avanços comportamentais e neurofisiológicos e ampliar a compreensão sobre os mecanismos de plasticidade neural e suas implicações no processo de aprendizagem.

Palavras-chave: Potenciais Evocados Auditivos. Processamento Espacial Visual. Percepção Auditiva. Estimulação Acústica. Reabilitação.

RESUMEN

Considerando la importancia de evaluar intervenciones auditivas para mejorar el aprendizaje, se objetivó investigar la eficacia de dos procedimientos terapéuticos, el Entrenamiento Auditivo Acústicamente Controlado (TAAC) y el Sistema de Estimulación NeuroAuditiva (SENA), analizados individualmente y en combinación, con el fin de verificar la influencia del orden de aplicación en los efectos de la estimulación. Para ello, se procedió a evaluar a 30 niños de 8 a 11 años, igualmente distribuidos por sexo y edad, mediante audiometría tonal, pruebas conductuales de procesamiento auditivo (escucha dicótica TDD, escucha monótica PSI, resolución temporal GIN y ordenación temporal TPD), potenciales evocados auditivos de corta (FFR) y larga latencia (P300), así como la Evaluación de la Percepción Visual (DTVP-2) y la Escala SAB, antes y después de las intervenciones. De este modo, se observó que, en la intervención aislada, el TAAC resultó eficaz en los procedimientos electrofisiológicos (FFR y P300), en las pruebas conductuales auditivas (PSI y TPD) y en la Escala SAB; mientras que el SENA mostró un efecto positivo en el FFR, en la prueba PSI y en el ítem 4 de la Escala SAB. Las intervenciones combinadas evidenciaron una mayor eficacia, especialmente cuando el TAAC se aplicó antes que el SENA, lo que sugiere que el SENA potencia los efectos del TAAC. Lo que permitió concluir que el uso combinado de ambos protocolos constituye un abordaje prometedor para la rehabilitación auditiva y cognitiva, al promover avances conductuales y neurofisiológicos, y ampliar la comprensión sobre los mecanismos de plasticidad neural y sus implicaciones en el proceso de aprendizaje.

Palabras clave: Potenciales Evocados Auditivos. Procesamiento Espacial Visual. Percepción Auditiva. Estimulación Acústica. Rehabilitación.

1 INTRODUCTION

The presence of normal auditory thresholds does not guarantee the ability to properly process and interpret verbal and nonverbal sounds. Many children diagnosed with central auditory processing disorder (CAPD) have alterations in auditory behavioral tests, as well as difficulties in language and cognitive processes, raising questions about the clinical validity of the diagnosis (Bellis; Jorgensen, 2014; Neijenhuis *et al*., 2019).

Central Auditory Processing (CAP) refers to the "Perceptual processing of auditory information in the central nervous system and the neurobiological activity responsible for the generation of auditory electrophysiological potentials" (ASHA, 2005). The British Society of Audiology (BSA) adds the participation of other neural processing systems that contribute to the modulation of *botton-up* processing (BSA, 2018). This definition evidences the participation of subcortical and cortical structures in the decoding and interpretation process of the fast and transient acoustic elements of speech and in the construction of learning, indicating the interference of PAC in language development (Martzog *et al*., 2019).

Individuals with CAPD have low performance in two or more auditory abilities: sound localization and lateralization, auditory discrimination, auditory pattern recognition, temporal aspects of hearing, figure-ground, auditory closure, binaural aspects of hearing (ASHA, 2005; Geffner, 2019). It is estimated that 2% to 5% of school-age children with learning complaints have primary CAPD, while in adults the prevalence can reach up to 17% between 50–54 years of age and exceed 70% after 60 years of age (Bellis; Jorgensen, 2014). Risk factors include prenatal/neonatal factors, recurrent otitis media, genetic factors, and neurological disorders (Chermak *et al*., 2014; Geffner, 2019).

The impact of CAPD on hearing, communication, and academic performance reinforces the need for interventions based on cognitive neuroscience, exploring the plasticity of the central nervous system (CNS) and promoting cortical reorganization, since improvements reflect on learning (De Wit *et al*., 2018). Auditory and cognitive training demonstrate positive effects on working memory and general cognition, although follow-up evaluation is recommended to verify long-term efficacy (Lawrence *et al*., 2018; Stropahl *et al*., 2020).

Several studies suggest that brainstem responses generate direct information about how the sound structure of a spoken syllable is decoded by the auditory system, highlighting the importance of the brainstem in decoding speech sounds (Skoe; Kraus, 2010).

Changes in CAP can be assessed by behavioral and electrophysiological testing. The behavioral battery investigates attention, organization, memory and perception of auditory details, with verbal and non-verbal, monaural or binaural stimuli. Electrophysiological tests complement the assessment, allowing the measurement of neuroelectrical activity and differentiating CAPD from other disorders, especially in children under seven years of age (ABA, 2016).

According to international and national recommendations, the evaluation of PAC should consist of a set of tests that evaluate monaural listening, dichotic listening, temporal ordering, temporal resolution and binaural interaction, considering the age, cognitive and linguistic development of the individual. Regarding the diagnosis of the disease, there is no unanimity regarding the characterization of the individual with CAPD (De Wit *et al*., 2018).

Auditory training protocols, especially combined with cognitive tasks, have been shown to improve auditory communication and functional skills, with greater benefit when associated with sensory rehabilitation or hearing aids. However, the long-term effects still need to be investigated (Stropahl *et al.*, 2020). Studies such as the one by Sharma *et al*. (2019) reinforce the importance of evaluating specific CAP tasks, such as the frequency pattern test, in children with reading or spelling disorders.

The NeuroAuditory Stimulation System (SENA) is a technology developed by Jordi Gazeran Expósito, by the Spanish company Sena System S.L.U. The project began in 2000, focusing on the relationship between hearing and learning difficulties. Its proprietary software was launched in 2005, evolving into a web platform in 2022, which integrates tools for assessment, stimulation and training of auditory skills, with an international presence in several countries, including Brazil. SENA emerges as a resource to assist existing treatments, incorporating digital technology into NeuroAuditory stimulation (SENA, 2022). As it is a relatively new procedure, studies are being carried out to reinforce the clinical findings, in the search for another resource based on scientific evidence.

In this context, the objective of the present study was to test the efficacy of TAAC and SENA, alone and in combination with each other, in schoolchildren with learning difficulties, analyzing whether the order of application influences the clinical results.

2 METHODOLOGY

2.1 PARTICIPANTS

The study included 30 children aged eight to eleven years, who met the inclusion criteria proposed for the study and were matched by age in the constitution of the groups. The sample was selected from among the patients treated at a speech-language therapy service in a public hospital in the city of São Paulo. The individuals presented characteristics resulting from risk factors (Table 2) important for learning disorders, with more than one risk factor per participant: genetic factors (73.3%), prenatal (26.6%), perinatal (26.6%), drug use during pregnancy (6.6%), neurological disorders (13.3%), metabolic disorders (6.6%) and emotional factors (86.6%).

The initial screening consisted of a brief anamnesis of the patient, to survey the audiological history, general health, use of medications, neurological and/or cognitive disorders. In addition, a basic audiological evaluation (pure tone threshold audiometry, vocal audiometry and immittance testing) was performed.

2.2 INTERVENTION PROGRAMS AND DISTRIBUTION OF GROUPS

The intervention program was carried out with three groups of patients: CONTROL (n=10), SENA (n=10) and TAAC (n=10), who were submitted to the NeuroAuditory Stimulation System (SENA) and the Acoustically Controlled Auditory Treatment (TAAC). The control group did not undergo treatments during the study, however, after its conclusion, all individuals received appropriate treatment, according to ethical and scientific principles. In the SENA and TAAC groups, two sequential stimulations were performed, evaluated at two different times.

The TAAC was adapted based on the methodology proposed by Ziliotto; Gil (2011). The tasks of each session of auditory training were organized with progressive complexity, starting with simpler stimuli and progressing to more difficult ones as the individual's performance improved. The signal-to-noise ratio followed the same principle, going from more favorable (positive) to less favorable (negative). The use of earphones allowed for separate training of the right and left ears. In the dichotic listening activities, the intensity of the main stimulus was maintained, and the intensity of the competitive stimulus was varied, which should be ignored. The tasks with verbal stimuli started with the right ear, and the non-verbal ones, with the left. During the sessions, the repetition of items was allowed when requested or indicated by the speech therapist. The criterion for increasing difficulty was to reach 70% or more of correct answers, and activities with less than 30% indicated the need to go back one level (Musiek; Schochat, 1998). The acoustically controlled auditory training was performed in ten weekly sessions of 45 minutes, totaling about eight hours of sensory stimulation, in a soundproof booth.

SENA used musical and speech stimuli, composed of excerpts from classical music (Mozart) and a narrative in Brazilian Portuguese told by a male announcer. These stimuli were modified by a frequency modulator that reduces bass sounds and intensifies high sounds, alternating with a low-pass system that regulates the speed of exchange between both, making stimulation intermittent and preventing habituation. The software has an equalizer that was activated in the stimulation of each individual at frequencies from 125 to

8000 Hz, with reference to the normal hearing pattern (0 dBHL). The maximum intensity did not exceed 90 dBNPS, with a mean volume of 60 dBNS per ear. The music and speech stimuli were mixed, and the same stimulus was presented in both ears via headphones (Sennheiser HD 559), whose harmonic distortion was <0.2% (1khz, 100dbspl) and a frequency response curve of 14 to 26KHz coupled to a traktor audio 6 analog digital converter (DAC). The stimulation occurred with the individual sitting, performing a motor activity (using a cell phone or tablet with the volume at zero), without reading or writing. Stimulation was performed in a quiet place, without interference from external noises. The protocol comprised 10 sessions of 45 min, with reprogramming after five sessions based on the audiological thresholds obtained through new audiometry and equalization and intensity adjustments, taking into account, in addition to the audiological thresholds, the individual sensitivity of each individual (SENA, 2022).

2.3 EVALUATION PROCEDURES

The following electrophysiological evaluation tests were used as study procedures: Brainstem Auditory Evoked Potential - BAEP P300 (Schochat, 2004) and *Frequency-Following Response* - FFR (Skoe; Kraus, 2010); *Gaps-in-noise* - GIN (Musiek *et al*., 2005), Pediatric Speech Intelligibility Test - PSI(MCI) (Ziliotto *et al.*, 1997), Duration Standard Test - TPD (Musiek *et al.*, 1990), Dichotic digit test - TDD (Collela-Santos; Pereira, 1997); visual perception assessment: Evolutionary Test of Visual Perception, second edition - DTVP-2 (Brown, 2002) and the SAB Scale - *Scale of Auditory Behavior* (Domitz; Schow, 2000). As described in Table 1, the study groups underwent an initial evaluation and evaluations with the study procedures at three different times: at the beginning of the intervention program, after each type of stimulation (SENA or TAAC) and at the end of the intervention program.

Table 1

Schedule of activities developed in the intervention programs

INTERVENTION PROGRAM					
Initial Assessment	Time 1	Stimulation	Time 2	Stimulation	Time 3
Consent form, Anamnesis, Diagnostic evaluation	Audiometric thresholds; Behavioral assessment of auditory processing: GIN, PSI-MCI, TPD, TDD; Behavioral assessment of visual perception: DTVP - 2; SAB Scale; Evaluation of short-latency (FFR) and long-latency evoked potential (P300)	SENA Group TAAC Group 10 sessions	Audiometric thresholds; Behavioral assessment of auditory processing: GIN, PSI-MCI, TPD, TDD; Behavioral assessment of visual perception: DTVP - 2; SAB Scale; Evaluation of short-latency (FFR) and long-latency evoked potential (P300)	TAAC Group SENA Group 10 sessions	Audiometric thresholds; Behavioral assessment of auditory processing: GIN, PSI-MCI, TPD, TDD; Behavioral assessment of visual perception: DTVP - 2; SAB Scale; Evaluation of short-latency (FFR) and long-latency evoked potential (P300)

Source: Prepared by the author

2.4 SAMPLE CHARACTERIZATION

The term "learning disabilities" involves multiple factors: cognitive, social, economic, physical, and mental, which are directly related to learning. The emotional and cognitive dimensions are profoundly affected by all these factors and exert an influence on student learning (Konstantinidis, 2024).

Thus, the following inclusion criteria were established for the composition of the sample of this study: presence of learning difficulties; hearing thresholds of up to 15 dB HL; age between 8 and 11 years; and changes in the assessment of auditory processing and visual perception. Individuals who presented evidence of neuropsychiatric conditions that could prevent the performance of the planned procedures were excluded, as well as those who were unavailable to attend the intervention sessions.

2.5 ETHICAL APPROVAL AND CONSENT

The study was approved by the institutional ethics committee under opinion number 2.521.264 and is registered in Plataforma Brasil under CAAE number 81971418.0.0000.5505. The national law was complied with and the appropriate ethical precautions were taken. The volunteers or their guardians signed a free and informed consent form, as well as a consent form.

2.6 STATISTICAL ANALYSIS

The continuous and semicontinuous data were initially compared with the Gauss curve, determining the normality for each variable. As the sample size in each group was considered small (n=10), parametric analysis was chosen. When the data had parametric behavior, mean and standard deviation were used, compared cross-sectionally by the unpaired Student's t-test. Categorical data were represented by absolute (n) and relative (%) frequencies and compared using Pearson's chi-square test. The correlation between the variables and continuous and semicontinuous data was performed using Pearson's correlation test. For all studies, the risk $\alpha \leq 0.05$ of committing a type I or 1st type error and a risk $\beta \leq 0.20$ of committing a type II or 2nd type error were considered. The SPSS 23.0 Statistics program (IBM)® and the FigurePad Prism 9.5 program (FigurePad Software, LLC) were used.

3 RESULTS AND DISCUSSION

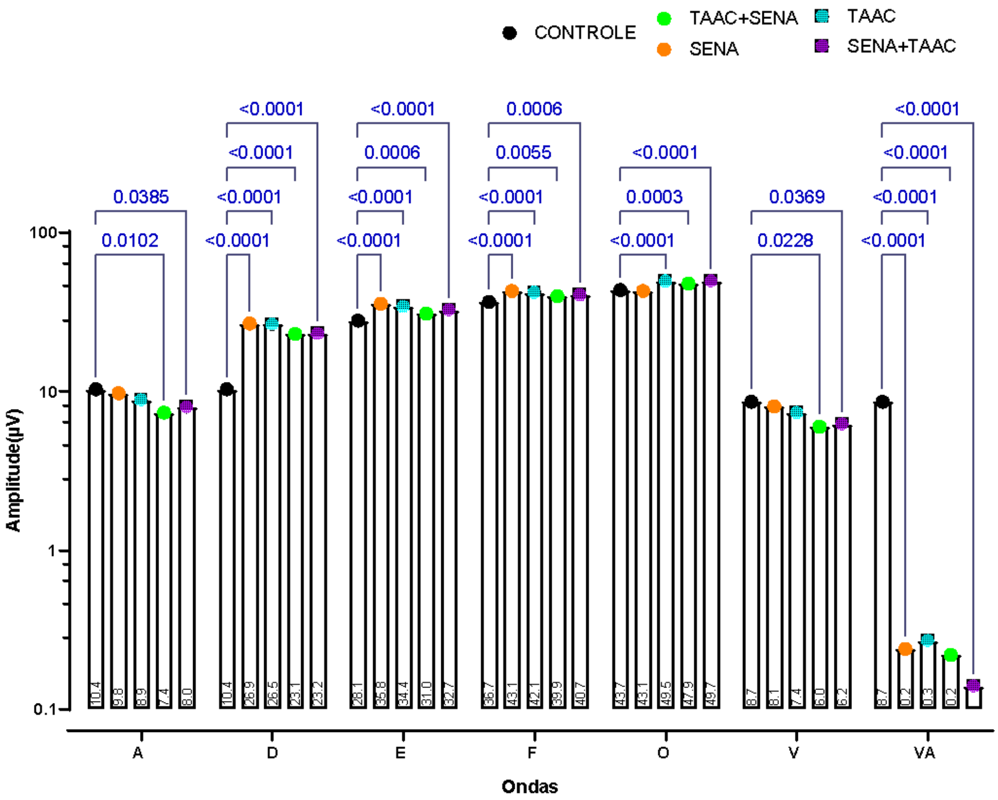
3.1 AUDITORY PLASTICITY: FFR RESULTS

The Frequency Following Response (FFR) is an auditory evoked potential that reflects the encoding of acoustic traces of the stimulus, especially speech sounds, in the nuclei of the auditory brainstem (Skoe; Kraus, 2010). FFR has a predominantly subcortical origin and its expression can be modulated by cognitive and attentional factors, especially in auditory learning contexts (White-Schwoch *et al.,* 2019).

As shown in Figure 1, the combined protocols (TAAC + SENA and SENA + TAAC) showed significant reductions in the latencies of waves V, A, D, E, F, O, and VA, with emphasis on the SENA + TAAC group in the VA complex (0.14 ms). These findings suggest that the combination of protocols promotes more efficient functional reorganization, possibly by synergistic activation of subcortical and cortical mechanisms, with SENA acting as an intensifier of the TAAC effect. The findings related to the VA complex, a marker of temporal accuracy and integrity of auditory response, reinforce the efficacy of the combination of protocols. The combined groups, especially SENA + TAAC, showed optimized performance, which suggests that the order of application can influence the efficiency of neural reorganization, although both combinations were effective.

Figure 1

Comparison between the Control, TAAC, SENA and combinations groups (TAAC+SENA; SENA+TAAC) for waves A, D, E, F, O, V, and VA of the FFR test



Legend: TAAC - Acoustically controlled auditory training; SENA – NeuroAuditory Stimulation System; FFR - *Frequency Following Response* . Data expressed as arithmetic mean marked with the statistical difference between groups through Two-Way Analysis of Variance with Fisher's post-test (LSD). P ≤ 0.05 was considered significant.
Source: Authors.

The TAAC and SENA groups alone did not show significant effects on waves V and A, which make up the *onset portion* and correspond to the plosive consonant /d/ (Kraus *et al.,* 2017), indicating that stimulation alone may not be sufficient to produce lasting effects at the subcortical level, reinforcing the concept that the density and complexity of the auditory stimulus are determinants for the induction of neural plasticity (White-Schwoch; Kraus, 2017). The combination of stimuli, with different rhythmic, frequencial and attentional characteristics, seems to increase the response capacity of the auditory system, promoting more evident functional reorganizations.

In waves D, E and F, all experimental groups showed significant differences in relation to the control group. The sustained portion (FFR) that occurs around 18 to 40 ms, composed of waves D, E and F, indicates the encoding of the periodic and harmonious sound structure of the vowel. Vowels are characterized by a long-lasting sound stimulus, being processed over a longer period. Waves D, E and F represent the fundamental frequency stimulus (F0), while the peaks between waves D and E represent phase blocking at the frequencies of the first formant (F1) and the peaks between waves E and F represent the frequencies of the second formant (F2). D, E, and F waves provide information about the neural phase-locking of the fundamental frequency and harmonic components of the stimulus (Skoe; Kraus, 2010). According to White-Schwoch; Kraus (2017), FFR has a "double face": it reveals both the effects of past auditory experiences and also the potential for future communicative development. The authors argue that FFR is a reflection of the auditory system's adaptations to significant sound exposure, arguing that rich, repeated, and engaging auditory experiences are crucial to shaping brainstem physiology.

For the O wave, which represents the coding of the *offset* (termination) of the sound stimulus, being one of the last waves to appear in the register, usually between 40 and 50 ms. It reflects the neural activity associated with the end of the vowel of the syllable, indicating late neural synchrony in the auditory pathway. The O wave is relevant because it provides information on the temporal precision in the closure of the acoustic stimulus (Skoe; Kraus, 2010; White-Schwoch *et al.*, 2019). In this study, in the isolated intervention, only the TAAC group presented statistically significant results. The effect of TAAC on the O wave may be related to the protocol's emphasis on temporal precision, rhythm, and fine acoustic discrimination tasks, which directly stimulate stimulus offset coding. Unlike SENA, which promotes alternating and diffuse auditory stimulation. TAAC requires active response and sustained focus, favoring delayed neural synchronization, explaining its efficacy in modulating this component of FFR (Skoe; Kraus, 2010; Kraus; White-Schwoch, 2015).

These findings indicate an improvement in neural synchronization and temporal accuracy of subcortical auditory processing, suggesting that the proposed interventions are capable of inducing functional plasticity in the auditory brainstem. This interpretation is supported by the literature that recognizes FFR as a sensitive marker of auditory experience and neural efficiency (Skoe; Kraus, 2010; White-Schwoch; Kraus, 2017).

The results confirm that combined auditory interventions are more effective than isolated interventions in modulating FFR and that the complementary use of SENA can potentiate the effects of TAAC. The data reinforce current models of auditory plasticity, which consider the auditory system as dynamic, distributed, and highly responsive to meaningful sound experience (White-Schwoch; Kraus, 2017; White-Schwoch *et al.*, 2019; Ross *et al.*, 2020).

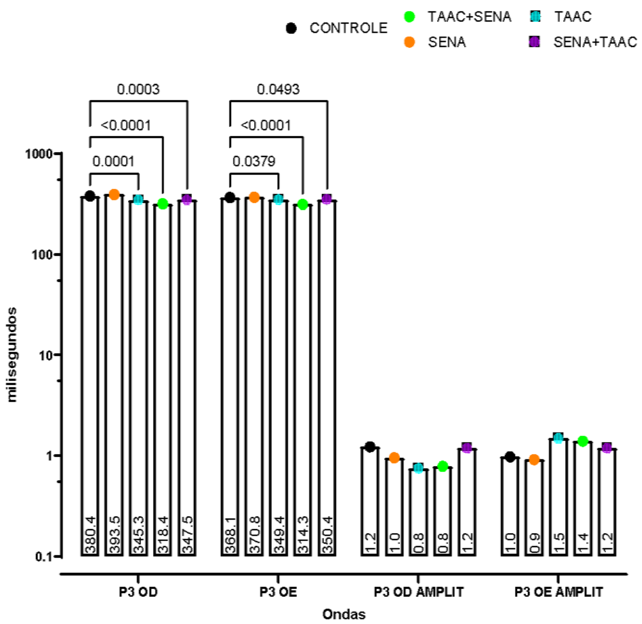
3.2 CORTICAL PROCESSES: P300 RESULTS

The PEALL P300 is a long-latency auditory evoked potential related to cognitive activities such as attention, discrimination, recognition, naming, and memorization of auditory information (Riggins; Scott, 2020). Its elicitation requires the performance of an active task by the individual, reflecting the functional use of the stimulus, so it is considered an endogenous potential. Its generators involve structures such as the auditory, prefrontal, centroparietal and hippocampal cortex, as well as associative regions such as the thalamus and temporoparietal cortex, interconnected to the brainstem and reticular formation (Sowndhararajan *et al.,* 2018).

P300 has been widely used as a complementary marker in the diagnosis and follow-up of cognitive and attentional alterations, as well as in monitoring the effectiveness of interventions such as auditory training (De Medeiros *et al.*, 2020). In the present study, the results of the P300 (Figure 2) showed that the SENA protocol, when applied in isolation, did not produce statistically significant changes in latency in any of the ears. On the other hand, TAAC alone generated significant bilateral improvement, demonstrating its effectiveness in modulating cortical activity.

Figure 2

Comparison of the Control, TAAC, SENA and combinations (TAAC+SENA; SENA+TAAC) for the P3 wave of the PEALL P300 test



Legend: TAAC - Acoustically controlled auditory training; SENA – NeuroAuditory Stimulation System; BAEP P300 - Long-latency auditory evoked potential; OD - Right ear; OE - left ear. Data expressed as arithmetic mean marked with the statistical difference between groups through Two-Way Analysis of Variance with Fisher's post-test (LSD). P ≤ 0.05 was considered significant.
Source: Authors.

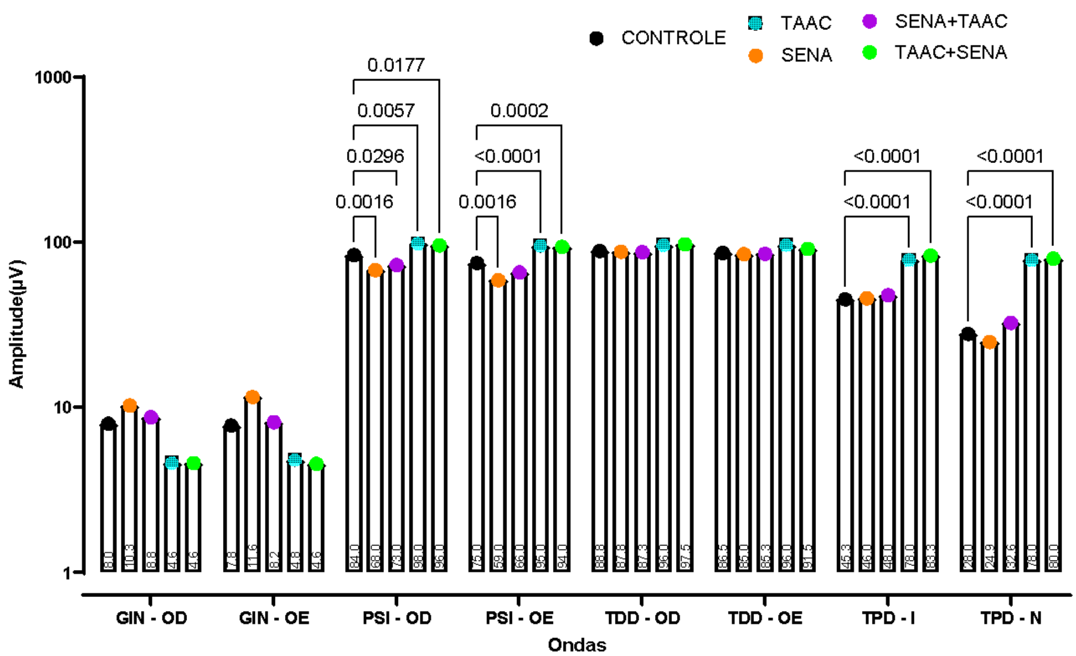
The combined protocols (TAAC + SENA and SENA + TAAC) also showed significant reductions in P300 latency, indicating a faster and more efficient cortical response. These findings suggest that, although SENA alone did not promote measurable changes in this electrophysiological marker, its association with TAAC potentiated the effects of auditory stimulation, especially with regard to the engagement of superior cortical mechanisms. This corroborates the idea that auditory interventions involving structured tasks and temporal control, such as TAAC, are more effective in promoting neural plasticity in regions associated with attention and auditory integration (Riggins; Scott, 2020; De Medeiros *et al.*, 2020). This result is particularly relevant in the context of children with learning difficulties, in whom deficits in temporal processing and low efficiency in the identification of brief and successive acoustic stimuli are frequently observed (Riggins; Scott, 2020).

3.3 CENTRAL AUDITORY PROCESSING (CAP)

Central auditory processing (CAP) has been widely studied and refers to the individual's ability to analyze and interpret auditory information effectively and efficiently. This process involves a set of fundamental auditory skills, such as sound detection, localization and discrimination, recognition, temporal ordering, figure-ground for verbal and non-verbal sounds, auditory synthesis, binaural integration, interaction and separation, auditory closure and recognition of temporal patterns. These skills are essential for understanding the acoustic stimuli captured by the peripheral auditory system (Avanzi; Cardoso, 2023). In the CAP tests (Figure 3), significant differences were observed in PSI, TPD, and TPD-N for groups with TAAC alone or in combination. The GIN and TDD tests did not show significant changes, indicating the absence of a measurable effect of the interventions in these aspects.

Figure 3

Comparison between Control, TAAC, SENA and combinations (TAAC+SENA; SENA+TAAC) in the GIN, PSI, TDD, TPD-I and TPD-N tests



Legend: TAAC - Acoustically controlled auditory training; SENA – NeuroAuditory Stimulation System; GIN – *Gaps-in-noise*; PSI - Pediatric Speech Intelligibility Test, TDD - Dichotic Digit Test; Duration pattern - TPD-I and TPD-N; OD - Right ear; OE - left ear. Data were expressed as arithmetic mean, marked with the statistical difference between groups through Two-Way Analysis of Variance with Fisher's post-test (LSD). P ≤ 0.05 was considered significant.
Source: Authors.

The PSI test evaluates figure-ground ability for verbal stimuli (Chermak *et al.*, 2014), showing that unsatisfactory performances may indicate difficulties in speech discrimination in noisy environments (Jerger *et al.*, 1983). Electrophysiological studies demonstrate that this ability depends on the efficient processing of acoustic information in the brainstem (Jerger; Jerger, 1982; Skoe; Kraus, 2010). In the present study, the SENA, TAAC and TAAC+SENA groups presented statistically significant results in the performance of this skill, suggesting an improvement in auditory segregation after the interventions. This finding may be justified by the fact that, in children, the auditory system is still in the process of maturation, which makes the PSI especially sensitive to detect alterations in populations with learning difficulties or language disorders (Schochat *et al.,* 2010). In addition, Vellozo *et al.* (2015) demonstrated that the PSI is applicable and effective in different age groups, with increasing performance as the central auditory pathway develops. The study also highlights its clinical value in school and therapeutic contexts. In the dichotic digit test (TDD) and GIN no significant differences were identified between the groups.

The Duration Pattern Test (DPT), which evaluates the ability of temporal ordering (Musiek *et al.*, 1990), can help in the assessment of the perception and processing of rapid temporal characteristics, including in children who already have a diagnosis of language impairment (Balen *et al.,* 2019; Pires; Schochat, 2019). In this study, statistically significant differences were observed, with better performances in the groups that included TAAC, especially when the intervention was initiated by it. The SENA group, alone, and the SENA + TAAC combination did not show significant improvement. The findings suggest that combined protocols, especially starting with TAAC, promote more expressive gains in auditory processing skills.

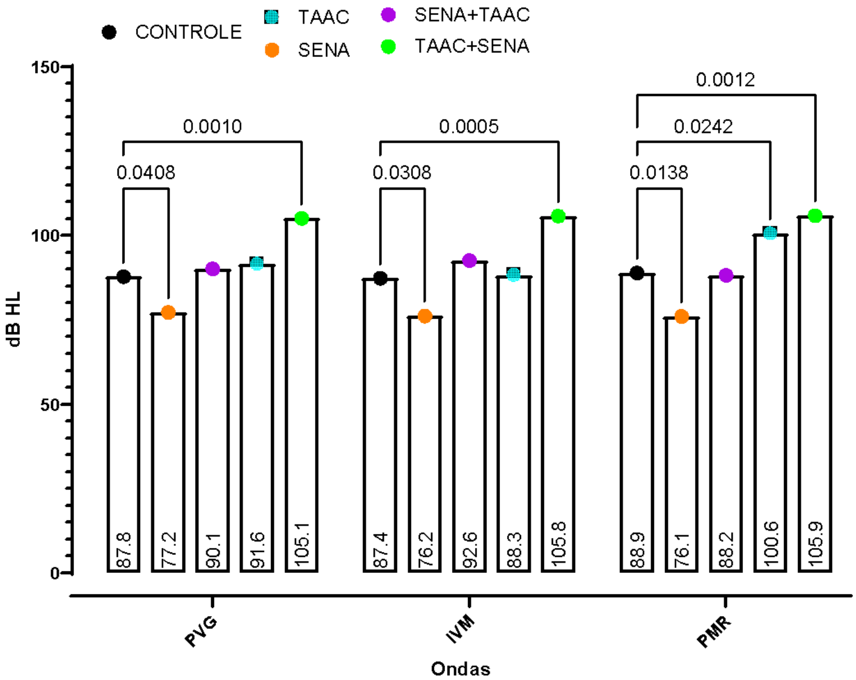
3.4 VISUOMOTOR SKILLS: DTVP-2

The *Developmental Test of Visual Perception – Second Edition* (DTVP-2) evaluates perceptual-visuomotor skills that are fundamental for school and daily performance. It is composed of functions of visual basis, position in space, figure-ground, visual closuring, and constancy of form, and functions that require integrated motor components, such as visuomotor coordination, copying, spatial relationship, and visuomotor velocity (Brown, 2002). According to Figure 4, the best results in the quotients general visual perception, visuomotor integration and reduced motor perception (PVG, IVM and PMR) were observed in the combined TAAC + SENA protocol, with statistical significance in all measures. The isolated TAAC group showed intermediate performance, superior to the control in some domains, but without robust differences. On the other hand, SENA, when applied in isolation, showed inferior results to the control group.

In addition, it was found that the order of application influenced the scores: when SENA was performed after TAAC (TAAC + SENA), the results were higher than with SENA alone, suggesting a possible synergistic or sequence-dependent effect. Although all experimental groups outperformed the control, only the TAAC + SENA combination promoted consistent and statistically significant gains.

Figure 4

Comparison between Control, TAAC, SENA and combinations (TAAC+SENA; SENA+TAAC) in the PVG, IVM and PMR subtests of the visual perception assessment



Legend: TAAC - Acoustically controlled auditory training; SENA – NeuroAuditory Stimulation System; PVG - general visual perception; IVM - visuomotor integration; PMR - perception of reduced motor skills. Data were expressed as arithmetic mean, marked with the statistical difference between groups through Two-Way Analysis of Variance with Fisher's post-test (LSD). $P \leq 0.05$ was considered significant.
Source: Authors.

The results obtained reinforce the influence of auditory and visual integration on learning. In natural environments, auditory signals are rarely processed in isolation, and are often accompanied by redundant or complementary visual information (Opoku-Baah, 2021). From a neurophysiological perspective, the inferior colliculus (IC) is known to receive visual inputs, with recent animal studies suggesting that these inputs increase sensitivity in auditory processing (Chen et al., 2019). In addition, vision plays a dominant role in auditory spatial plasticity, guiding the maturation of auditory neuron response properties and ensuring the alignment of spatial maps in the superior colliculus (Opoku-Baah, 2021).

In the school context, visuomotor integration is equally decisive, since the efficiency of learning depends largely on the proficiency of this skill, built on postural and body bases from the first years of life. The perception of reduced motor skills, assessed by the DTVP-2, reflects precisely the sum of the scores obtained between visual perception and the visuomotor component, pointing to the relevance of this integration in learning (Opoku-Baah, 2021).

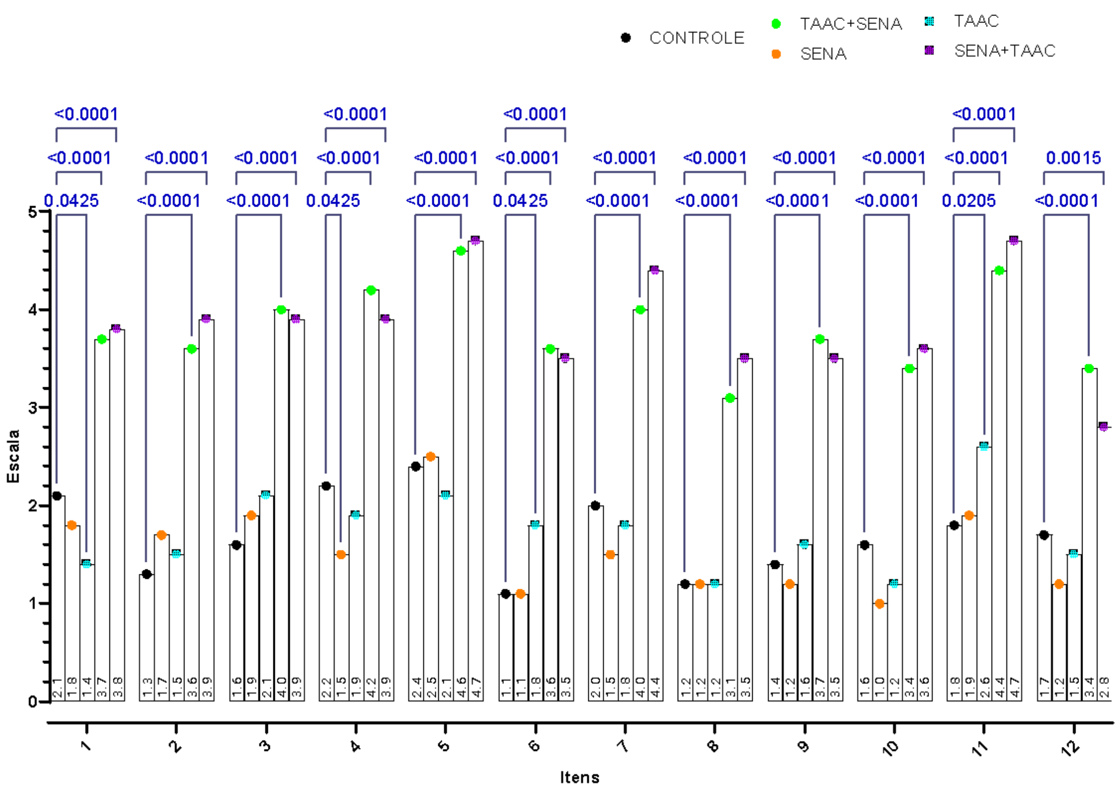
Thus, the superiority of the TAAC + SENA protocol may be related to the combination of auditory and visual stimuli that strengthens connectivity between brain areas and recruits wider networks, resulting in more accurate and stable perceptions (Opoku-Baah, 2021). Using training methods based on complementary stimuli can enhance both auditory perceptual learning and visuomotor development, which justifies the more expressive gains in the combined group.

3.5 FUNCTIONAL AUDITORY BEHAVIOR: SAB SCALE

The SAB Scale is a questionnaire that allows quantifying, in the perception of parents and/or guardians, the child's auditory behavior in the demands of daily life, considering the information received through hearing (Viacelli *et al.*, 2018). In this study, a significant improvement was observed in all 12 items evaluated in the groups submitted to hearing interventions, with emphasis on the combined protocols, which promoted broader benefits in the auditory behavior perceived or reported by caregivers, compared to the isolated interventions (Figure 5).

Figure 5

Comparison between Control, TAAC, SENA and combinations (TAAC+SENA; SENA+TAAC) in the 12 items of the SAB Scale



Legend: TAAC - Acoustically controlled auditory training; SENA – NeuroAuditory Stimulation System; SAB Scale - *Scale of Auditory Behavior*. Data expressed as arithmetic mean marked with the statistical difference between groups through Two-Way Analysis of Variance with Fisher's post-test (LSD). P ≤ 0.05 was considered significant.
Source: Authors.

Recent studies reinforce the sensitivity of the SAB Scale to detect functional changes after intervention. In a study with children with auditory processing disorder, parents or guardians reported significant evolution in the hearing and attention domains after training with TAAC, evidencing the scale's ability to reflect perceived gains in daily life (Viacelli *et al*., 2018). In addition, a study with adolescents indicated good agreement between self-perception and parental assessment through the SAB and correlation with results obtained in formal auditory processing tests, validating the use of the instrument as a diagnostic support (Nardez *et al.,* 2022). The consistency of the scores across the different domains of the scale in this study reinforces the effectiveness of integrated protocols in promoting functional auditory skills in the family and educational environment.

3.6 NEUROFUNCTIONAL INTEGRATION: LURIA'S THEORY

According to Luria (1981), conscious brain functioning results from the integration of three functional units, understood as complex systems that articulate several brain areas in a dynamic way (Mikadze *et al*., 2019; Peña-Casanova, 2018). The first unit, responsible for regulating cortical tone, wakefulness, and attention, is supported by subcortical structures such as the brainstem, reticular formation, and mesial regions of the cortex, with connections to the limbic system (Peña-Casanova; Sigg-Alonso, 2020). The second unit, dedicated to receiving, processing, and storing sensory information, involves the temporal, parietal, and occipital lobes (Peña-Casanova; Sigg-Alonso, 2020; Sugahara *et al*., 2021), where stimuli are organized and subsequently converted into thought and memory in the tertiary cortex (Sugahara *et al*., 2021). Finally, the third unit, which will not be discussed in the context of this study, is related to the frontal lobes and refers to the programming, regulation, and verification of conscious activity, including functions such as impulse inhibition, planning, and monitoring of actions (Ramos-Galarza *et al*., 2019).

In this sense, the hypothesis raised in the present study about the efficacy of SENA is based on the first functional unit described by Luria, which plays a fundamental role in the regulation of the state of cortical activity and the level of vigilance. This stimulation would favor the activation of subcortical circuits responsible for neural readiness, establishing a state of greater cortical organization necessary for the processing of auditory information (Peña-Casanova; Sigg-Alonso, 2020). Thus, SENA would act as a neurosensory preparer, contributing to the modulation of cortical arousal and primary care. The results obtained in the ipsilateral PSI tests in both ears, in the VA complex in the FFR and in item 4 of the SAB scale after the application of the SENA corroborate Luria's statements regarding the importance of subcortical regulation for attention and sensory processing.

In turn, the TAAC (Acoustically Controlled Auditory Training) protocol establishes a direct relationship with the second functional unit. Its structure requires the active execution of auditory tasks with a high degree of temporal and acoustic control, stimulating cortical regions involved in the analysis, discrimination and interpretation of sounds, especially the temporal and parietal lobes (Peña-Casanova; Sigg-Alonso, 2020; Sugahara *et al*., 2021). By reinforcing sequential processing and auditory coding, TAAC contributes to the enhancement of perceptual and cognitive skills related to language and central auditory processing, strengthening the sensory systems that underpin learning. Clinical evidence shows that the protocol promotes significant improvement in children with central auditory processing disorder, especially in the areas of attention, listening, and communicative behavior (Viacelli *et al*., 2018).

4 CONCLUSION

The study evaluated the effectiveness of TAAC and SENA protocols in children with learning disabilities. Applied alone, TAAC showed significant effects on central auditory processing and P300, while SENA showed more restricted but relevant gains in FFR markers and the PSI test, suggesting initial action on neural readiness and primary care. These results reinforce the complementarity of the protocols, with TAAC activating structured tasks with high temporal demand and SENA modulating subcortical activity and increasing neural responsiveness.

The combined interventions promoted superior and consistent effects in multiple domains, including subcortical neural synchronization, cortical plasticity, perceptual-visuomotor skills, and functional auditory behavior, as evidenced in electrophysiological and perceptual tests, and on the SAB scale. Although the order of application did not impact all electrophysiological markers, better performance was observed in auditory processing tests when TAAC preceded SENA, indicating that the sequence can enhance certain gains.

The results highlight the combined use of the protocols as a promising approach for auditory and cognitive rehabilitation, expanding the understanding of the mechanisms of neural plasticity and its implications for learning.

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