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MISCELLANEOUS

Evaluation of central auditory processing skills in children with stuttering

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Abstract

Purpose This study aimed to evaluate central auditory processing skills in children with stuttering.

Methods Twenty children with stuttering (CWS) group (3 females, 17 males) and 20 Typical Development (TD) group children (7 females, 13 males) with normal pure-tone hearing were given the Frequency Pattern Test (FPT) and Duration Pattern Test (DPT), Filtre Words (FW), Auditory Figure-Ground (AFG), Competing Words (CW) and Competing Sentences (CS) tests used in Central Auditory Processing (CAP).

Results No significant difference was found in either group's FW, AFG, and CS tests. However, there was a significant difference between the scores obtained from the FPT, DPT, and CW tests. FPT and DPT results revealed a significant difference between the frequency and duration pattern scores of children in the CWS and TD groups ($p<0.001$). Statistical comparisons of right–left ear difference scores between the CWS and TD groups were conducted for the SCAN-C subtest for DW, with significant differences ($p<0.01$). Children with stuttering scored lower on these tests compared to typical development.

Conclusion The observed pattern of results characterized by deficits in FPT, DPT, and dichotic auditory tasks aligns with theoretical models that implicate interhemispheric transfer in stuttering. Based on our behavioral data, we propose a hypothesis: the core difficulty may not lie in right-to-left hemisphere transfer, but in the longer loop of left-to-right and back again, potentially introducing critical timing delays in sound processing. It is recommended that interhemispheric training be implemented as part of stuttering interventions.plemented as part of stuttering int

Keywords Central auditory processing disorder · Child · Childhood stuttering · Temporal processing

Introduction

Central auditory processing (CAP) involves the coordinated transmission and processing of auditory information between the hemispheres. In this process, stimuli from the right ear are transmitted directly to the left hemisphere of the brain. In contrast, stimuli from the left ear are first transmitted to the right hemisphere and then to the left hemisphere via the corpus callosum. Recognition of sounds takes place in the right hemisphere, while detailed analysis is performed when this data is transmitted to the left hemisphere. In the final stage, the Broca area transforms auditory information into motor speech output, resulting in fluent speech. This bidirectional interhemispheric transmission mechanism plays a critical role in auditory-verbal integration. CAP also involves listening to and understanding speech in environments with multiple sound stimuli daily. These processes include accurately processing sounds reaching both ears simultaneously, separating them from environmental noise, identifying speech sounds, determining which words these sounds belong to, and analyzing sound sequences within words. Disorders in central auditory processing mechanisms can lead to difficulties in comprehension, especially during listening (e.g., particularly in challenging listening

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environments) [1]. The neurofunctional basis of interhemispheric auditory processing is fundamental to understanding the specialization of auditory cortical regions and their roles in perceiving complex auditory stimuli. The prevailing model suggests that the right auditory cortex is specialized in processing spectral information, such as pitch and melody. In contrast, the left auditory cortex is more adept at managing rapid temporal details, which are crucial for speech perception [2, 3].

Fluent speech is achieved by producing each speech sound in the words that make up the sentence at the appropriate frequency, with a certain level of intensity and duration. This process is realized through the coordinated movement of articulatory structures. The smooth, rhythmic, and uninterrupted expression of speech sounds is the basis of fluency. Conditions in which this fluency is disrupted, especially speech patterns characterized by repetitions, prolongations, or blocks at the sound, syllable, or word level, are clinically defined as stuttering (dysfluency) [4].

It has been stated that auditory processing disorder, especially in terms of temporal auditory processing functions, is one of the possible causes of stuttering [5]. In addition, it has been suggested that auditory temporal processing disorder may affect stuttering through mechanisms such as disrupting auditory feedback to the speech control centers of the brain, causing instability in neural representations of speech sounds, and causing sensory-motor inconsistencies in the speech control process [6]. Recent research has provided compelling evidence regarding the functional profiles of the cerebral hemispheres in children who stutter, specifically highlighting unique deficits in the left hemisphere and enhanced functionality in the right hemisphere. Neuroimaging studies have consistently shown that the left hemisphere, typically dominant in language tasks, demonstrates abnormal activation patterns among children who stutter, particularly in critical areas such as Broca. This disruption is often reflected in decreased activation during speech tasks, negatively impacting language production. Enhanced brain activity in Broca's area has been observed in subjects treated with risperidone, indicating its critical role in speech production. Additionally, insufficient left hemisphere cortical areas—especially the inferior frontal and ventral motor cortices, essential for fluent speech—have been associated with stuttering [7, 8]. This insufficient activation suggests that the left hemisphere's role in language generation is compromised, which is critical in stuttering. Specifically, studies have shown that individuals who stutter exhibit decreased activation in key left-hemisphere regions critical for speech production, particularly during speech-related tasks. Notably, these regions include the inferior frontal gyrus and ventral motor cortex, which are crucial for generating fluent speech [9, 10].

Evidence from neuroimaging studies supports the assertion that the left hemisphere's involvement in speech processes is significantly altered in individuals who stutter. For example, deactivation patterns within the auditory cortex of adults who stutter have been observed, particularly in tasks that require speech processing, where the expected left-hemispheric advantage is weakened or absent [11].

Speech production in adults who stutter engages both cerebral hemispheres, with right hemisphere activity potentially contributing significantly to maintaining speech fluency. During speech tasks, these individuals exhibit reduced activation in auditory regions alongside increased activity in premotor and motor areas. Furthermore, fluent speech production involves complex functional dynamics between the cerebral hemispheres [12]. This pattern reflects the broader understanding that abnormalities in the left hemisphere may lead to increased reliance on right hemisphere regions for compensatory mechanisms during speech production.

Stuttering is a developmental disorder that affects speech fluency. It occurs in 5% preschool children and 1% adult population [13]. Despite this prevalence, the mechanisms underlying stuttering have not been fully elucidated. This study used frequency and duration discrimination, dichotic word and sentence, filtre word, and auditory figure-ground tests to evaluate the possible relationship between stuttering and central auditory processing. In particular, the dichotic word test measures interhemispheric transmission, i.e., the transfer of information between the right and left cerebral hemispheres, by simultaneously presenting different sounds to both ears and providing information about the level of auditory development and maturation [14].

Materials and methods

Subjects

The study included 40 children aged 6 to 11 years, comprising 20 Children with Stuttering (CWS) group (3 females, 17 males; mean age = 8.05 ± 2.76 years) as well as a control group of 20 Typical Development (TD) group children (7 females, 13 males; mean age = 8.50 ± 2.27 years) with no developmental, intellectual, or speaking issues. All children were monolingual native speakers of Turkish. Although formal socioeconomic status (SES) matching was not conducted, the groups were drawn from comparable community backgrounds, minimizing the likelihood of significant socioeconomic disparities that could affect auditory processing performance.

The CWS group was referred to the clinic for stuttering (syllable/word repetitions, blocks) or speech rate/rhythm disorders based on parent/teacher reports. Other types of

speech disorders (e.g., mispronunciation and speech delay) were excluded from the study. The CWS group was evaluated by the research's speech pathologist using the Turkish version of the Stuttering Severity Instrument, 4th edition (SSI-4-TR) [15]. Pure tone hearing thresholds of all participants were measured as < 20 dB HL in the range of 250–8000 Hz and confirmed to be within the normal hearing range. The study included children who were not diagnosed with any neurodevelopmental disorder such as autism spectrum disorder (ASD), attention deficit hyperactivity disorder (ADHD), or intellectual disability (ID) in parent/teacher reports and hospital records. Children were administered frequency and duration patterns, auditory figure-ground, and Competing word and sentence tests used in CAP.

Informed consent was obtained from the parents of the participants.

The evaluation procedures were approved by the hospital's Medical Ethics Committee of the Gazi University Clinical Research Ethics Committee (study number: 2022.509) in Turkiye, and written informed consent was obtained from all participants.

Auditory processing tests

Children wore headphones and were presented with test items at their most comfortable hearing level. Although the most comfortable hearing level (MCL) was determined individually for each participant to ensure optimal test conditions, the resulting presentation levels consistently fell within a standardized, clinically normal range (approximately 40–60 dB HL) for all children. The child responded according to the instructions. Correct responses were scored for stimuli presented separately to each ear (right or left) in the tests. The study compared the correct scores of children with and without stuttering in CAP tests.

Temporal auditory processing was examined using the Frequency Pattern Test (FPT) and Duration Pattern Test (DPT). The stimuli were tones at 880 Hz and 1122 Hz, both lasting 200 ms, having an interstimulus period of 150 ms and a rise/fall duration of 10 ms, known as FPT. Also, 3-tone stimuli of long (500 ms) and short (250 ms) durations, called DPT, were presented at 300ms intervals [16, 17].

Children were assessed using four subtests of the Scan-C test. The Filtre Words (FW) test assesses the subject's ability to process speech when the signal is distorted or transmitted in a poor acoustic environment. The Auditory Figure Ground (AFG) test captured monosyllabic syllables using a multi-talker voice babble noise with a signal-to-noise ratio of + 8 dB. The test assesses the ability to detect speech sounds in noisy environments. The Competing Words (CW) test shows the level of interhemispheric (corpus callosum) processing auditory development and auditory maturation, the processes by which the right and left hemispheres transfer messages to each other. Different words were presented to both ears at the same time. Children were instructed to respond to stimuli presented separately to each ear (right/left). Correct responses were scored depending on which ear they were given. In the Competing Sentences (CS) test, separate stimuli are simultaneously delivered to the right and left ears. Performance on the Competing Sentences Test reflects the maturation of the auditory nerve system, as it requires efficient interhemispheric processing [1, 14]. In the CS test, children were asked to repeat the sentence in the left ear when they heard the sentence presented to the right ear in the first stage and the sentence in the right ear when they heard the sentence presented to the left ear in the second stage. This method was designed to measure interhemispheric communication (Fig. 1).

Statistical analysis

Continuous data were summarized using descriptive metrics such as standard deviation, mean, median, minimum, and maximum values. Discrete data were expressed as counts in percentage form. The normality of continuous data was assessed using the Shapiro-Wilk test. Group comparisons of test scores employed the Mann-Whitney U test, and age was compared using the independent samples t-test. The Wilcoxon test was used to compare scores between the right and left ears. The z statistic from the Mann-Whitney U and Wilcoxon test was used to calculate the effect size.

Formula: $\frac{z}{\sqrt{n}}$

Afterward, small, medium, and high effects were interpreted according to 0.1, 0.3, and 0.5 intervals. Chi-square and Fisher's Exact tests were utilized for comparisons involving nominal variables (cross-tabulations). Data analyses were performed using IBM SPSS version 20 (Chicago, IL, U.S.A.), with statistical significance established at $p < 0.05$.

Results

The mean age of the participants was 8.05 ± 2.76 years in the CWS group and 8.50 ± 2.27 years in the TD group. The groups were comparable in terms of age distribution, with no significant difference between the mean ages of the CWS and TD groups (Independent Samples t-test, p = 0.580). Similarly, the sex distribution between the groups did not differ significantly (Chi-Square Test, p = 0.144). Given the absence of significant age differences and the use of a relatively constrained age range (6–11 years), the primary group

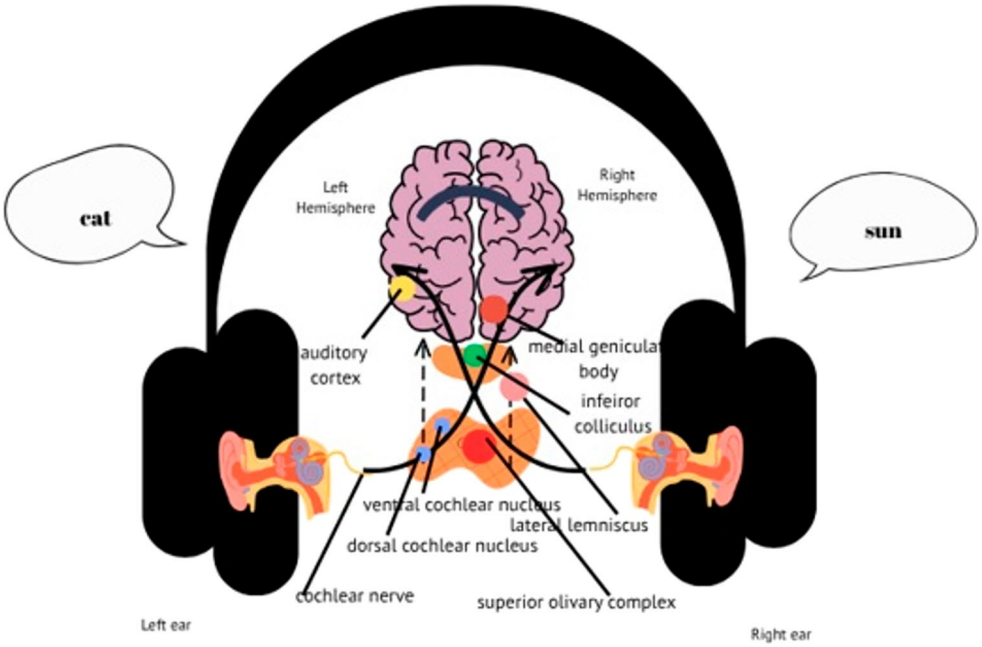


Fig. 1 This schematic illustration depicts the dichotic listening procedure, in which two different words are presented simultaneously—one to the left ear and the other to the right ear. The participant's task is to say the words they hear or perceive during each trial. In the example, the word / cat/ is presented to the left ear and /sun/ to the right ear

comparisons for auditory processing tasks were conducted using Independent Samples t-tests without including age as a covariate. Syllable repetitions were the most common symptom in the CWS group (60%), with a moderate stuttering score. Stuttering score was objectively measured using the SSI-4-TR. The mean total severity score obtained was 2.68 ± 1.08 (Mean ± SD). This score corresponds to 'moderate severity' stuttering according to the classification in the scale manual. The distribution of individual scores ranges from [Min: 1, Max: 5].

Spearman's rank correlation coefficient was used to assess the relationship between the total scores on the SSI-4-TR and the performance on the CAP tests. A negative correlation was found between SSI-4-TR scores and Dichotic Sentences test difference scores (r = -0.482, $p < 0.05$). In the CWS group, as SSI-4-TR test scores increase, dichotic sentence difference scores decrease.

A significant difference was found in Frequency Pattern Test (FPT) and Duration Pattern Test (DPT) scores between the CWS group and typically developing (TD) peers ($p < 0.001$), with the CWS group scoring lower on both tests. The effect size for this difference was high.

Analysis of SCAN-C subtest ear difference scores revealed no significant intergroup differences in Filtered Words (FW), Auditory Figure–Ground (AFG), or Competing Sentences (CS) ($p > 0.05$). However, a significant difference was observed in Competing Words (CW) ear difference scores ($p < 0.01$), where the CWS group exhibited higher right–left ear difference scores than the TD group, with a medium effect size.

The data presented in Table 1 summarizes the statistical comparisons of both groups.

The findings revealed that children with fluency disorders' temporal auditory and dichotic processing skills differed from their typically developing peers.

Discussion

Our findings suggest that weaknesses in frequency, duration, and dichotic processing may reflect delays in interhemispheric processing. The basis of this situation is the different processing abilities of each hemisphere specific to cognitive functions. While the left hemisphere plays a dominant role in tasks with high temporal-duration resolution, the right hemisphere processes more efficiently in tasks that require spectral resolution of frequency components. In this context, synchronization between the left and right hemispheres is critical in the holistic processing of frequency and temporal information [1]. Recent studies have indicated that frequency and duration perception difficulties can significantly impact speech fluency in children who stutter. For example, Lescht et al. demonstrated that children who stutter exhibit difficulties in processing the temporal aspects of language, which can lead to challenges in producing fluent speech. However, their findings primarily focused on declarative memory rather than temporal aspects of speech [18]. Furthermore, findings by Aydin Uysal et al. highlighted that phonetic complexity can exacerbate disfluency, implying a relationship between speech production and processing weaknesses in children who stutter [19]. On the other hand, dichotic listening tasks, which involve simultaneous auditory stimulation to both ears, have been shown to reveal asymmetries in hemispheric processing in individuals who

Table 1 Descriptive statistics of the measured parameters and outcomes of the statistical analyses conducted between the experimental groups

	CWS group	TD group	*P*-value	Effect size
	Mean ± SD Median (Min-Max)	Mean ± SD Median (Min-Max)		
Age (year)	8.05 ± 2.76 8.0 (6–11)	8.50 ± 2.27 8.5 (6–11)	0.580	---
FPT	6.60 ± 4.05 6 (1–15)	13.65 ± 2.15 14 (9–17)	< 0.001 *	0,72
DPT	5.75 ± 4.02 4.5 (0–18)	14.20 ± 1.76 14 (12–17)	< 0.001 *	0,77
FW R-L Ear Δ	2.25 ± 2.29 2 (0–8)	1.50 ± 1.27 1 (0–4)	0.417	---
AFG R-L Ear Δ	2.30 ± 2.02 2 (0–7)	2.30 ± 1.52 2.5 (0–5)	0.678	---
CW R-L Ear Δ	7.60 ± 5.66 6 (0–20)	3.00 ± 1.68 3 (0–5)	0.001 **	0,49
CS R-L Ear Δ	3.65 ± 2.83 3 (0–9)	2.00 ± 1.52 2 (0–4)	0.076	---

There was no significant difference in age distribution between the groups ($p = 0.580$, Independent Samples t-test). Comparisons between groups were made with the Mann-Whitney U test. Effect size (r) was calculated using the formula $z/\sqrt{n}$ ($|r| \geq 0.1$: small effect; ≥ 0.3: medium effect; ≥ 0.5: high effect). *$p < 0.001$, **$p < 0.01$ were considered significant. R-L: Right-Left, Δ: Difference score

stutter. It is reported that children who stutter tend to demonstrate weaker interhemispheric connectivity during non-speech motor tasks, particularly in lower frequency bands, indicating that altered connectivity may hinder their ability to process language and auditory cues effectively, potentially contributing to disfluency [20].

Another study reported that auditory temporal processing skills were weaker in children with developmental stuttering compared to their peers without stuttering. The poor performance on the duration pattern test in children with stuttering suggests that difficulties in temporal processing skills may play a role in the pathophysiology of stuttering. This finding supports theories about the relationship between stuttering and neural timing disorders. It supports the variability in duration and frequency patterns obtained in the present study. Furthermore, it has been suggested that reduced left hemisphere dominance in individuals with stuttering may contribute to delays in speech production and fluency disorders [16]. Similarly, the differences observed in the dichotic listening tests in the present study may be related to possible deficits in brain lateralization and auditory-motor integration.

The observed frequency, duration, and dichotic processing deficiencies suggest a broader impairment in integrating information across the hemispheres. Research by Zaky et al. emphasizes that stuttering is accompanied by rapid language development in preschool years. When these developmental milestones are disrupted, it can lead to enduring challenges in speech and language fluency [13]. Using auditory processing tests, this study investigated the possible relationship between central auditory processing disorder (CAPD) and stuttering. Structural features that distinguish the auditory system from other sensory systems were considered in this context. Unlike other systems, the auditory system is not only a transversal system; it has both contralateral and ipsilateral inputs to the cortex. The key to the contralateral effect in the auditory system is that most of the fibers entering the cortex are contralateral [21]. During daily speech perception, contralateral nerve fibers contribute to 80% of the processing, while ipsilateral nerve fibers account for 20%. Ipsilateral and contralateral processes and central auditory processing functions perform dichotic listening processes in daily life [22]. As described in the literature, during dichotic stimulation, auditory signals to the ear are first analyzed in the cochlear nucleus, then travel through the superior olivary complex, the inferior colliculus, and the medial geniculate body in the thalamus via both ipsilateral and contralateral pathways, terminating in the primary auditory cortices of the cerebral hemispheres. However, the contralateral pathways are more powerful and predominant; therefore, auditory stimuli are usually represented more effectively in the opposite hemisphere. In this process, the transfer of auditory information between both hemispheres occurs through the corpus callosum. In particular, the need to transmit language-related stimuli from the left ear first to the right hemisphere and then to the left hemisphere via the corpus callosum makes the functional integrity of this structure critical. Therefore, although there are different theoretical models, dichotic listening performance is primarily based on the functional competence of the corpus callosum [23].

The behavioral findings obtained in this study indicate impaired auditory processing skills in the CWS group. Directly investigating the underlying neural mechanisms of this impairment will be a crucial next step in this field. For example, functional Magnetic Resonance Imaging (fMRI)

can be used to visualize differences in the connectivity between the auditory cortex and speech-motor networks in these children [24]. Similarly, event-related potentials such as the Mismatch Negativity (MMN) [25] and the P2 component [26] may reveal fundamental electrophysiological deficits in auditory discrimination and classification. Future neurophysiological research of this kind may validate the neural basis of the behavioral deficits observed in the present study and deepen our understanding of the neurobiology of stuttering.

Moreover, Neef et al. provided insights into altered structural connectivity between the left and right inferior frontal cortices. It may contribute to delays in interhemispheric processing, indicating a fundamental neurological basis underlying stuttering [27]. Neef et al.'s fMRI study provides objective evidence of impaired motor-auditory integration by demonstrating functional differences in the left motor cortex during speech in individuals with stuttering [28]. This finding supports that stuttering is a behavioral symptom and a disruption in neural processes. Similarly, Jansson-Verkasalo et al. examined the relationship between stuttering and central auditory processing disorders in children through mismatch negativity (MMN) responses. They found atypical sound-processing patterns in the auditory cortex of children with stuttering [29]. Both studies contribute to developing new approaches to diagnosing and treating the disorder by evaluating the neurobiological basis of stuttering with objective neuroimaging and electrophysiological methods. Elhakemm et al. reported that the P2 component, in particular, showed longer latency and lower amplitude in children with stuttering [30]. These findings suggest delays in the cortical processing of auditory information, which may affect speech-motor planning. It is consistent with the differences in brain lateralization observed in dichotic listening tests. Etchell et al.'s systematic review comprehensively analyzed neuroimaging studies on developmental stuttering between 1995 and 2016, revealing consistent findings. The study highlights differences in brain structure and function in individuals with stuttering (e.g., decreased gray matter in left frontal and temporal regions, abnormal activation in the basal ganglia). It suggests that disruptions in motor planning, auditory feedback, and attention networks play critical roles in the pathophysiology of stuttering [31]. This review provides strong evidence that stuttering results from the dysfunction of multiple neural networks, placing the motor-auditory integration disorders described by Neef et al. and Jansson-Verkasalo et al. in a broader context. It also highlights the need for standardized protocols for future research, noting the inconsistent findings across different age groups [28, 29, 31]. Such meta-analyses reinforce the importance of neuroscientific data in understanding the heterogeneous nature of stuttering and guide the development of individualized intervention strategies in clinical practice.

Central auditory processing tests provide important information in determining poor, impaired, or normal functioning of the individual's auditory system. This information plays a critical role in planning and directing stuttering therapy. The findings of our study suggest the presence of temporal and dichotic processing deficits in a subgroup of stutterers. Therefore, we recommend CAP evaluation, especially in individuals with persistent stuttering. In patients with CAPD, integration of auditory temporal training and dichotic listening exercises into speech therapy may be tried. In those without CAPD, traditional fluency therapies should be prioritized. However, randomized controlled trials are needed to test the effectiveness of these recommendations.

Limitations

A significant limitation of this study is the sex imbalance within the participant groups. While every effort was made to recruit a balanced sample, practical constraints resulted in a higher proportion of males, which reflects the higher prevalence of stuttering in the male population. Although our preliminary analyses did not reveal a significant main effect of sex on the primary outcome measures within our sample, the unbalanced design limits the generalizability of our findings. Future studies with larger, sex-matched cohorts are essential to confirm our findings and to elucidate the potential role of sex differences in the auditory processing profile of children who stutter. The generalizability of the present findings is limited by the modest sample size ($n=20$ per group). Although this provides adequate power for the primary group-level comparisons, it precludes more nuanced analyses of potential subgroups based on factors such as age, sex, or stuttering severity. Therefore, this study should be considered preliminary, and its primary value lies in generating robust hypotheses for future investigations with larger cohorts. Moreover, an important limitation of our study is that a standardized test battery could not be used to diagnose CAPD. In future studies, it is recommended that individuals with stuttering symptoms be initially evaluated with a standardized CAP screening test battery, and diagnostic tests should be applied to those identified as being at risk through screening.

Funding None.

Data availability Data will be made available on a reasonable request.

Declarations

Ethical approval Approved by the Gazi University Hospital's Medical Ethics Committee of the Clinical Research Ethics Committee (study

number: 2022.509) in Turkiye.

Informed consent Informed consent was obtained from all participants in the study.

Conflict of interest None.

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