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Passive hearing abilities of dyslexia children: Investigating the rumble frequency of skull bones cavity

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Dyslexia is a specific learning disorder characterized by difficulties with accurate spelling, poor fluency, and decoding abilities. This study investigated the passive hearing abilities and sound conduction through skull bone resonance in dyslexic children to determine the relationship between skull and sinus hearing ability. Thirty children diagnosed with dyslexia according to DSM-5 criteria were selected, and their skull bone resonance was measured using a customized bone conduction microphone and preamp microphone affixed to the forehead. Results showed that 73.3% of the dyslexic children had abnormal sound conduction, categorized into damping (31.3%), resonance (18.2%), and rumbling (50%) abnormalities. Significant lateralization differences were found, with more abnormalities on the right side of the skull. The frontal, maxillary, and mastoid sinuses exhibited damping, resonance, and rumbling abnormalities, with rumbling being the most significant finding (38.2%). The study suggests that phonological deficits in dyslexia may be attributed to skull involvement in fine auditory processing, and the condition of skull bone cavities and sinuses might play a role in the phonological processing of dyslexic children. The findings highlight the importance of investigating skull sinus conditions as a potential factor affecting sound processing in neurodevelopmental disorders.

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1. INTRODUCTION

Dyslexia is a specific learning disorder characterized by difficulties in accurate spelling, reading fluency, and decoding abilities[1]. In Egypt, the prevalence of dyslexia among primary school children has been reported to be 11.7% [2]. Globally, dyslexia affect between 5% and 17% of school-aged children, depending on the population studied [3]. Practical classifications of dyslexia are based on the dominant type of cognitive impairment [4]. Among these, phonological dyslexia is considered the most prevalent, surpassing both visual (orthographic) and mixed types [5].

Cognitive skills are the most extensively studied aspect of dyslexia, including deficits in auditory frequency discrimination, perception of amplitude modulation, stream segregation, and spatial sound processing [6]. A comprehensive review of potential causes of dyslexia highlighted the significance of auditory and visual sensory perception in the development of reading difficulties. However, it concluded that most current research remains at a superficial level and lacks a thorough understanding of the underlying sensory processing deficits [7,8,5].

Most existing studies have focused on central neural mechanisms, including reduced activation in specific brain regions [9] and dysfunctions at the brainstem level [10]. Fewer studies have addressed peripheral auditory structures, and only limited attention has been given to the role of the inner, middle, and outer ears in dyslexia [1,11]. Notably, the influence of skull bone structure and sinus cavities on sound conduction has been largely overlooked in current literature, despite their possible role in shaping auditory perception.

This study aims to address this gap by evaluating passive auditory transmission and skull bone resonance in children with dyslexia by examining passive hearing and sound conduction via skull bone resonance in children with dyslexia. We hypothesize that children with dyslexia may present with pathological or morphological differences in the skull sinuses that influence their auditory processing. By analyzing the resonance of skull bone cavities, this research aims to determine whether abnormalities in sinus and skull structure contribute to phonological deficits. Understanding this potential link may provide a new, non-invasive, and cost-effective pathway for early identification and intervention in children with dyslexia.

2. METHODOLOGY

A. STUDY DESIGN AND PARTICIPANTS

This cross-sectional study enrolled 30 children (22 males, 8 females), aged 6 to 14 years, diagnosed with specific learning disorder (dyslexia) according to Diagnostic and Statical Manual of Mental Disorder, 5th edition (DSM-5 2013) [12], from December 2023 to July 2024 who demonstrated average intellectual functioning. Children with hearing impairments, craniofacial anomalies (such as dwarfism or achondroplasia), or a history of ear or skull surgeries were excluded. Participants were recruited from the Special Needs Children Care Center at the Faculty of Postgraduate Childhood Studies, Ain Shams University, Cairo, Egypt. The study received ethical approval and adhered to the principles outlined in the Declaration of Helsinki.

B. APPARATUS AND MATERIALS

In this study, children were seated individually in a sound-isolated RC25 room to minimize external acoustic interference. They were exposed to continuous broadband Gaussian noise emitted from a standard loudspeaker positioned one meter away. The noise stimulus covered a frequency range from 20 Hz to 20,000 Hz and was presented at an intensity of 70 dB HL. An array of microphones was employed: two air-conduction microphones were placed near the external ear canal openings to capture signals transmitted via air pathways, while six bone-conduction microphones were affixed to anatomical landmarks corresponding to the frontal, maxillary, and mastoid sinus regions to record cranially transmitted acoustic energy. Second, using a flexible rubber grommet to ensure firm contact and minimize air leakage. Signal acquisition via an STM32 microcontroller, sampling at 48 kHz with 24-bit resolution.

The recorded signals were analyzed using Short Time Fourier Transform (STFT) techniques. A Hanning window function was applied to minimize spectral leakage and enhance frequency resolution. enhance the fidelity of frequency domain representation. A 1000 ms window with a 10 ms frame shift was used, resulting in a 99% overlap. This setting allows high frequency resolution while maintaining temporal continuity Spectral [13]. energy was evaluated across standardized octave bands ranging from 63 Hz to 16 kHz, aligning with conventional acoustic analysis protocols, consistent with conventional octave-band analysis standards in acoustics.

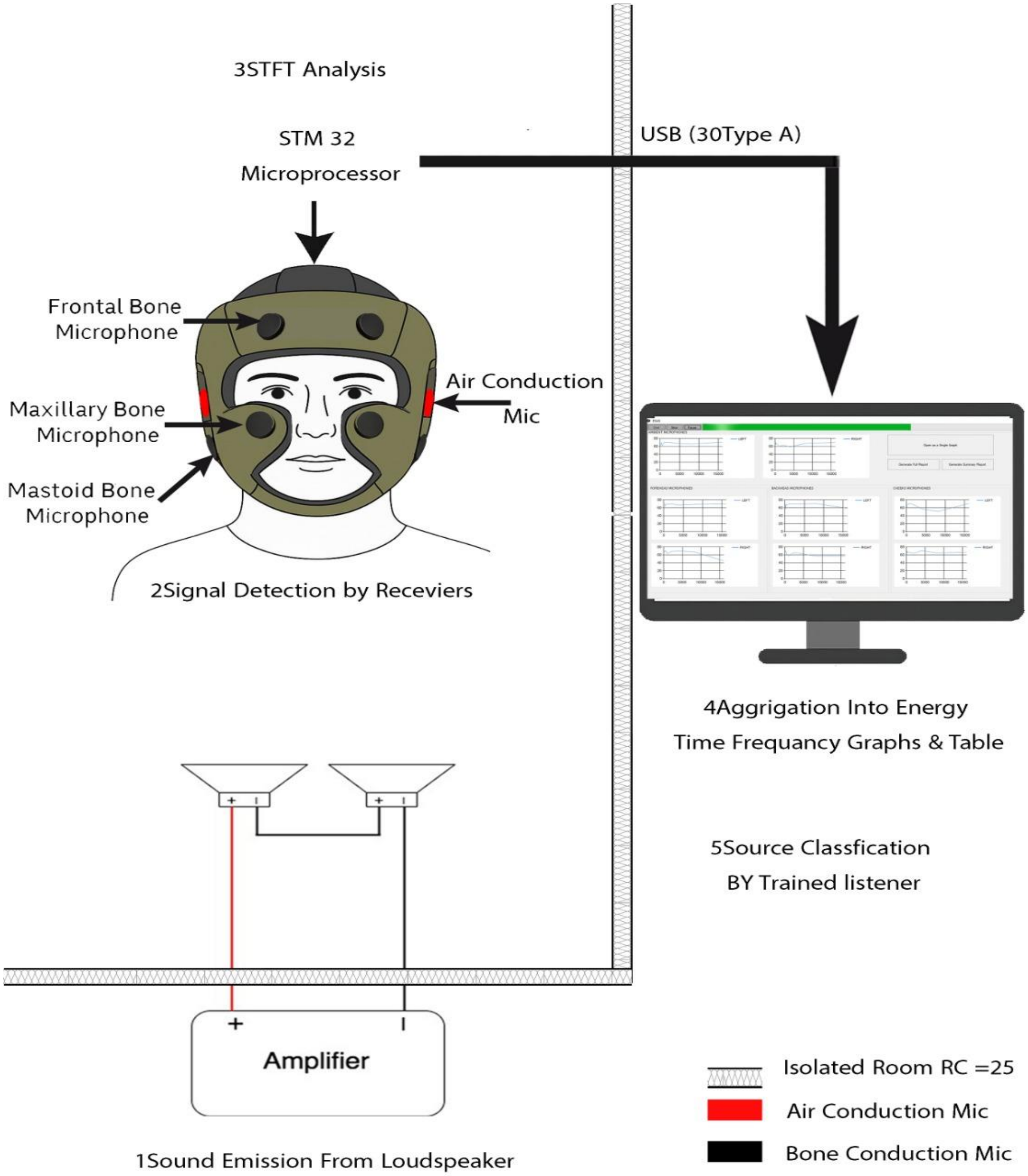

Figure 1. The acquisition device illustrating the test procedures

C. TEST PROCEDURES

The experimental protocol proceeded through multiple structured steps. Initially, the sound radiated from the loudspeaker was detected by the microphone array. Subsequently, the recorded signals underwent STFT analysis to extract energy distributions across both time and frequency domains. The resulting spectral data were compiled into graphical and tabular representations to illustrate the energy present at each time-frequency point. These representations were then aggregated (Aggregation refers to the temporal stacking of frequency components to extract dominant energy trends over time)[14] to reconstruct the overall energy distribution throughout the recording session. Finally, source classification techniques were applied to differentiate valid sinus resonance signals from potential artifacts such as environmental noise or mechanical disturbances, audio signals were screened manually by a trained listener. In cases of artifact detection, the measurement was repeated, thereby ensuring the integrity and reliability of the data.

This structured methodological approach enabled the specific characterization of resonance phenomena within the nasal sinuses, providing a detailed understanding of their acoustic

behavior under controlled broadband excitation.

1- Sound Emission from loudspeaker (20-20000 Hz, 70dB HL) → 2-Signal detection by receivers (around the cranial region) → 3-Short-time Fourier transform (STFT) analysis of received signal → 4-Aggregation into energy – time freq. graphs and tables → 5-Source classification (To identify valid signals and Eliminate Noise)

Figure 2. Block diagram of the measurement and data collection process steps

D. ESTIMATION OF RESONANCE FREQUENCIES

In this paper, we also calculated as shown in table 1The initial resonance frequency for each cavity was determined using cavity size data from [15] in their study, "Assessing Volume Growth of Paranasal Sinuses and Nasal Cavity in Children Using Three-Dimensional Imaging Software”. For enhanced accuracy, this study also considered the findings of [16,17,18], who measured the normal sinus cavity in children according to sex and age. The quality of changes between two ages was calculated as a relative difference between the averages of volumetric indices at the beginning and end of each stage. We calculated the cavity volume according to sex and age as V1, representing the geometric equivalent of the three dimensions, which were constructed to estimate size variation.

$$V1 = \sqrt[3]{(length\ x\ breadth\ x\ height} \qquad (1)$$

And using the equation of:

$$f_{\ resonance} = \frac{v}{2\pi}\sqrt{\frac{A}{VL}} \qquad (2)$$

where v = 344 m s^{-1} is the speed of sound, A is the area of the opening, L is the length of the nasal cavity port, and V is the volume of the air enclosed.

Table 1: The resonance frequency of skull cavities (Frontal, Maxillary, and Mastoid sinus) as the volume calculated from three-dimensional imaging in children according to age and sex difference

	Male			**Female**		
Age	**Frontal cavity Freq. (Hz)**	**Maxillary cavity Freq. (Hz)**	**Mastoid cavity Freq. (Hz)**	**Frontal cavity Freq. (Hz)**	**Maxillary cavity Freq. (Hz)**	**Mastoid cavity Freq. (Hz)**
5, 6	5,363	1,772	1,313	1,899	1,822	2,092
7, 8	5,363	1,408	1,313	2,118	1,639	2,334
9	5,363	1,412	1,313	2,184	1,662	2,367
10	5,363	1,412	1,313	2,184	1,372	2,367
11	5,363	1,255	1,313	2,190	1,329	2,292
13	1,621	1,157	929	2,104	1,185	2,202
14	1,621	1,157	929	2,028	1,142	2,122
15	1,621	1,157	929	1,959	1,103	2,050

This finding is consistent with CT-based calculations showing that resonance frequency differences between boys and girls are not due to sinus volume but rather due to differences in sinus port length and area (L and A), where boys typically have wider and shorter ports, significantly affecting resonance frequency according to the Helmholtz formula [19,20].

3. RESULTS

The information and analysis of the results had been obtained from sample of thirty (30) children, diagnosed as Specific Learning Disorder (SLD) (Dyslexia) according to DSM-5. Twenty-two (22) males, and eight (8) females, with age range from 6-14 years old, were divided into two groups: group of dyslexic children showed normal sound conduction of passive hearing abilities based on the skull bone cavities response to Gaussian noise (20-20,000 Hz, 70 dB HL). The number of this group were eight (n=8), 6 males and 2 females, six dyslexic children in the normal sound conduction group ranged from 6-9 years with mean 8.33 (±1.2), while two children ranged from 10-14 years with mean 12.75 (±1.7). In this study, we compared the sound frequency considered as “normal” sound conduction of passive hearing abilities based on the skull bone cavities’ response to Gaussian noise, to the “normal” sound frequency calculated based on three-dimensional neuroimaging of the skull sinuses according to age.

The result shows no significant difference ($p < 0.05$), as seen in Table (2), denoting the coincidence of the sound frequency based on Gaussian noise response and the sound frequency based on 3D neuroimaging of the skull’s frontal, maxillary, and mastoid sinuses. We showed that the acoustic characteristics determined by the two methods are typically statistically matched, providing high accuracy and reliability of the measured skull bone cavity technique.

Table 2: comparison between normal cavity frequency of left and right Frontal, Maxillary, and Mastoid sinus cavity and the calculated standard frequency in each sinus of the eight dyslexic children according to their age

Age	**6**	**8**	**9**	**9**	**9**	**9**	**11.5**	**14**	**Z test**	**P value**
Cavity freq. frontal (Lt.)	5368	5365	5367	5368	2184	2188	5366	1627	1.498	0.134
Cavity freq. frontal (Rt.)	5368	5366	5368	5366	2188	2189	5367	1628	1.603	0.109
Calculated standard Frontal	5363	5363	5363	5363	2184	2184	5363	1621		
Cavity freq. Maxillary (Lt.)	1771	1410	1414	1419	1662	1672	1258	1155	0.316	0.752
Cavity freq. Maxillary (Rt.)	1771	1409	1419	1418	1666	1677	1256	1155	0.421	0.674
Calculated standard Maxillary	1772	1408	1412	1412	1662	1662	1255	1157		
Cavity freq. Mastoid (Lt.)	1313	1317	1315	1315	2367	2366	1313	925	0.660	0.509
Cavity freq. Mastoid (Rt.)	1313	1318	1315	1319	2366	2369	1314	925	1.025	0.305
Calculated standard Mastoid	1313	1313	1313	1313	2367	2367	1313	929		

The other group of the results was the group of dyslexic children who showed abnormal sound conduction of passive hearing abilities based on the skull bone cavities response to Gaussian noise (20-20,000 Hz, 70 dB HL).

This group consisted of twenty-two children with dyslexia (n= 22), 16 males, and 6 females. Thirteen children, age ranged from 6-9 years with mean 7.92 (±2.1), and 9 children their age ranged from 10-14 years with mean 10.50 (±1.6) as shown in table (3).

Table 3: Shows Age, and Sex differences of normal and abnormal sound frequencies based on the skull bone cavities response to Gaussian noise in children with Dyslexia.

	Normal sound Freq. (N=8)				**Abnormal sound Freq. (N=22)**			
Age	**N**	**%**	**Mean**	**SD**	**N**	**%**	**Mean**	**SD**
6-9	6	75%	8.33	1.21	13	59.1%	7.92	2.17
10-14	2	25%	12.75	1.76	9	40.9%	10.50	1.62
Total	8	100%	9.43	2.38	22	100%	8.97	2.23
Sex	**N**		**%**		**N**		**%**	
Male	6		75%		16		72.7%	
Female	2		25%		6		27.3%	

Furthermore, the abnormal sound conduction group (n=22) were categorized into three different distinguished groups including: the “Damping” abnormality group showed frequency ranging between (20-500 Hz) (low frequency ranges), the “Resonance “abnormality group (2KHz-20KHz) (High frequency ranges). “Rumbling” abnormality group at frequency (20-500 Hz) and (2KHz-20KHz) (low and high frequency ranges).

As regards sex difference, males in the damping group were (n=5) (31.3%), resonance group were (n=3) (18.8%), and Rumbling group were (n=8) (50%) of the male group (n=16), while the females were (n=2) (33.3%) in damping group, and (n=2) (33.3%) in resonance group, and (n=2) (33.3%) in rumpling group of significance difference (p=0.03) showing more abnormality of the skull bone cavity resonance in boys.

As regards age groups, the younger group age ranged from 6-9 years (n=13), the damping abnormality were (n=5) (38.%), resonance abnormality (n=2) (15.4%), and rumbling abnormality (n=6) (46.2%), while the elder group age ranged from 10-14 years (n=9), the damping abnormality (n=2) (22.3%), resonance abnormality (n=3) (33.3%), while rumbling abnormality (n=4) (44.4%) showing no significance difference between younger and elder age groups (p=0.4) while the highest percentage of abnormality was the rumbling abnormal sound frequency.

As regards the skull sinuses (Frontal, Maxillary, and Mastoid), the total abnormalities of the sound frequencies, (Damping, Resonance, and Rumbling) on the right-side sinuses of the skull (n=55). Damping abnormality on right side sinuses were (n=12) with (21%), Resonance (n=14) with (25.5%), while rumbling (n=21) with (38.2%) with highly significant difference with (P=0.001) towards the rumbling abnormality, while the total abnormalities of the sound frequencies on the left side sinuses of the skull (n=14), damping abnormality on the left side sinuses were (n=6) with (42.9%), resonance (n=0) with (0%), while rumbling (n=0) with (0%) with no significant difference for (P=0.3). Results showed highly significant right side skull rumbling sound abnormality, as shown in table (4). Extreme values were used to reflect peak resonance. All tables now describe frequency bands and statistical values explicitly.

Table 4: Shows the abnormal sound frequencies damping, resonance, rumbling abnormalities on right and left skull lateralization of %the Frontal, Maxillary, and Mastoid Sinus

Sample Variables	**Damping**		**Resonance**		**Rumbling**		**All (d+res+rum)**		**(res+rum)**		**χ^2**	**p-value**
	N	**%**	**N**	**%**	**N**	**%**	**N**	**%**	**N**	**%**		
Frontal (Rt)	4	18.2	5	22.7	7	31.8	1	4.5	2	9.1	7.444	0.1 NS
Frontal (Lt)	2	9.1	0	0	0	0	1	4.5	2	9.1	13.866	0.008 HS
Maxillary (Rt)	4	18.2	5	22.7	7	31.8	1	4.5	2	9.1	7.444	0.1 NS
Maxillary (Lt)	2	9.1	0	0	0	0	1	4.5	2	9.1	13.866	0.008 HS
Mastoid (Rt)	4	18.2	4	18.2	7	31.8	0	0	2	9.1	7.683	0.1 NS
Mastoid (Lt)	2	9.1	0	0	0	0	1	4.5	2	9.1	12.897	0.02 S
Total Right side of the Skull Sinuses	12	21.8	14	25.5	21	38.2	2	3.6	6	10.9	19.636	0.001 H.S.
Total Left side of the Skull Sinuses	6	42.9	0	0	0	0	2	14.2	6	42.9	2.286	0.3 NS

*d = damping, res = resonance, rum = rumbling

4. DISCUSSION

This study aimed to utilize an acoustic cavity resonance measurement technique to explore anatomical and pathological variations affecting the nasal and paranasal sinuses in a safer and easier manner compared to conventional X-ray and CT imaging.

Our findings highlighted the role of skull bone cavity resonance in children with dyslexia, a previously under-investigated area. Approximately 73% of dyslexic children in our study exhibited abnormal passive sound transmission patterns through the skull cavities, consistent with previous reports of altered auditory processing in this population [21,22]. Traditionally, based on the conventional theory of speech sound production, the acoustical function of the paranasal sinuses has been considered secondary as side branches. However, [23], in their study "Acoustic Analysis of Detailed Three-Dimensional Shape of the Human Nasal Cavity and Paranasal Sinuses," suggested that the paranasal sinuses contribute to the generation of sound peaks, implying that they act not only as side branches but also as resonators. This finding aligns with studies showing that more dyslexic children than controls demonstrated clinically significant reductions in dichotic listening performance, although no consistent pattern of deficit emerged [24]. Further studies using direct sweep-tone measurements of nasal tract transfer functions also indicated that nasal sinuses should be considered as a relevant part of the acoustic system. The addition of at least two shunting cavities to the nasal structure in models of the speech organs was shown to improve the spectrum for nasals and nasalized vowels at lower frequencies [25].

These findings suggest that anatomical or pathological variations affecting skull cavity acoustics may contribute to the phonological processing difficulties commonly observed in dyslexia, which is an important factor underlying or associated with reading impairments in this population [26].

In this study, three types of abnormalities were detected: damping (31.8%), resonance shifts (27.2%), and rumbling (40.9%). These results suggest that physical or pathological changes affecting sinus morphology or cavity media may be present in dyslexic children. Medical research on nasal sinuses has explored various pathological conditions that could interfere with normal sound wave propagation in the skull cavity, reproducing damping, resonance, and rumbling effects:

- Damping abnormalities may result from air-fluid levels or complete opacification due to sinusitis, commonly observed in 60% of sinusitis cases, particularly in maxillary and frontal sinuses [27]. Sinusitis affects about 5% of children aged 5–9 years and 15% of adolescents, with a higher prevalence in males [28]. The presence of fluid significantly influences acoustic wave propagation by enhancing attenuation through increased interaction with the fluid medium [29,30].
- Resonance shifts are likely due to alterations in sinus port dimensions. Studies have shown that frontal and maxillary sinus volumes may increase as a compensatory mechanism following severe nasal septal deviation (NSD). The frequency of NSD is about 86.6% and increases with age, predominantly in males [31,32,33]. An enlarged cavity lowers the natural resonance frequency, allowing longer wavelength sound waves to resonate more effectively, resulting in louder perceived sounds[34].
- Rumbling patterns represent complex acoustic phenomena, likely due to cavity interference effects. Sinus mucosa thickening is one of the most common sinus pathologies, with a reported frequency between 34% and 66%, and the membrane thickness reaching 2–4 mm in many cases [35]. Irregular or rough wall surfaces disrupt uniform sound propagation, causing scattered reflections that manifest as phase irregularities and low-frequency rumbling sounds [34]. Furthermore, septa formation within the sinuses due to embryological development can create multiple coupled resonators, leading to complex sound wave interactions and rumbling effects [36,37].

Additionally, the "Fizz sign" - the presence of gas bubbles within the sinuses - is often indicative of acute sinusitis [38]. From an acoustic perspective, these gas bubbles disrupt normal sound propagation, leading to complex scattering and secondary wave generation known as acoustic cavitation, contributing to rumbling or buzzing sounds [39].

Significant sex differences were observed in this study, with males showing a higher prevalence of sound conduction abnormalities (72.7%) compared to females (27.3%). This aligns with epidemiological data indicating that dyslexia is more prevalent among males, with odds ratios ranging from 1.5:1 to 3.3:1 [26,40]. Sexual dimorphism in auditory cortex anatomy and hemispheric asymmetry has been reported in dyslexia, especially in males [41]. These anatomical differences may contribute to the higher rates of paranasal sinus pathologies observed in males before puberty. Additionally, male skull cavities tend to be larger, leading to variations in the location and size of sinus ostia, which can affect sound conduction [42.]

This finding is consistent with CT-based calculations showing that resonance frequency differences between boys and girls are not due to sinus volume but rather due to differences in sinus port length and area (L and A), with boys typically having wider and shorter ports, significantly affecting resonance frequency according to the Helmholtz formula.

Regarding lateralization, a right-side predominance of abnormalities was evident. Abnormalities were more frequent on the right side for damping (21.8%), resonance shifts (25.5%), and rumbling (38.2%), while damping was higher on the left side (42.9%) with no resonance or rumbling abnormalities recorded. This difference was statistically significant ($p = 0.001$).

This lateralization pattern supports classical theories such as Orton's (1937) "lateralization theory of dyslexia," which postulated deviant cerebral lateralization in dyslexic children. More recent studies have confirmed relationships between lateralization patterns and reading impairments [43,44]. Anatomical studies have also shown a predominance of right-sided frontal sinus pathology [45,46] and septal deviations resulting in asymmetric mastoid sinus volumes favoring the right side [47].

Future research should integrate acoustic assessments with imaging techniques to better map the anatomical correlates of resonance abnormalities. Longitudinal studies are also needed to determine whether skull resonance profiles could serve as early biomarkers for dyslexia and related neurodevelopmental disorders.

5. LIMITATIONS AND FUTURE DIRECTIONS

This study has several limitations:

- The relatively small sample size limits the generalizability of findings, necessitating replication in larger, more diverse cohorts.

- A control group of typically developing children, matched for age and sex, was not included, which is important for validating resonance pattern findings.
- Direct comparisons between resonance frequency abnormalities and pathological findings from neuroimaging were not conducted.
- High-resolution imaging (e.g., CT scans) was not performed to confirm anatomical variations directly.
- Comorbid conditions such as allergic rhinitis, which may affect sinus resonance, were not systematically excluded.

6. CONCLUSION

This study investigated the passive hearing ability and sound conduction using skull bone resonance in 30 children diagnosed with dyslexia. The results showed that 73.3% of children with dyslexia had abnormal sound conduction, categorized as damping (31.3%), resonance (18.2%), and rumbling (40.9%) abnormalities. Significant lateralization differences were observed with more abnormalities on the right side of the skull. The frontal, maxillary, and mastoid sinuses exhibited damping, resonance, and rumbling abnormalities, with rumbling being the most significant finding. This study suggests that phonological deficits in dyslexia may be attributed to skull involvement in fine auditory processing and highlights the importance of investigating skull sinus conditions as a potential factor affecting sound processing in children with dyslexia. The skull bone cavity resonance measurement technique can be utilized in specialized cranial cavities, providing a safer and more convenient method of assessment, as this technique is particularly beneficial for pediatric patients as it does not involve radiation exposure. Furthermore, it is a cost-effective approach, where the skull bone cavity resonance measurement technique can be effectively employed in cases of pediatric disorders, requiring only 5-10 minutes with minimal regulatory requirements and precautions.

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DECLARATION

This manuscript is original and has not been published or submitted for publication elsewhere. The content of this manuscript is the result of our research, and all sources of information have been acknowledged. All the authors contributed significantly to the research and preparation of this manuscript. Below is a summary of the contributions of each author

Author 1: [Ibrahim EL Noshokaty], Author 2: [Howida El Gebaly], Author 3: [Manal Omar]

All authors were equally responsible for the content and integrity of this study. All the authors have read and approved the final version of the manuscript and represent honest work.

CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest to declare. All co-authors have seen and agree with the contents of the manuscript and there are no financial interests to declare. We certify that the submission is original work and is not under review by any other journal.

ETHICS APPROVAL

FPGCS-ASUREC/RHDIRB2020110401/MSDFC-9/11/2023-S9. The FPGCS- ASU REC was organized and operated according to the guidelines of the Declaration of Helsinki and The Islamic Organization for Medical Science.

DATA AVAILABILITY

The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request

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