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The Influence of Hearing Aid Type on Reading: Results of an Eye-Tracking Study at University

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Abstract

Background/Objectives: The study examines the characteristics of reading written texts depending on the type of hearing aid (monaural or binaural) and the individual hearing compensatory device used (cochlear implant or hearing aid) by students studying engineering fields of study in inclusive higher education. **Methods:** The identification of the students' characteristics of reading was carried out using an eye-tracker. **Results:** The data obtained by eye-tracking technology indicate that there are no significant differences in the gaze point indicators when reading everyday text between students with binaural hearing aids and students without hearing impairments. At the same time, students with monaural cochlear implants showed different gaze point indicators when reading everyday text compared to the results of groups of students without hearing impairments and students with binaural hearing aids. Significant differences were found in indicators related to pupil diameter, in particular between the groups of students with monaural cochlear implants and students with binaural hearing aids. **Conclusions:** The results demonstrate the need to adapt written teaching materials not only to take into account the characteristics caused by the hearing impairment itself, but also to take into account individual characteristics caused by the type of hearing aid.

Keywords: eye-tracking; reading; students with hearing impairments; hearing impairment; monaural hearing aids; binaural hearing aids; cognitive load; cognitive characteristics; educational materials

1. Introduction

Effective teaching of students with hearing impairments is impossible without specially prepared educational conditions and materials tailored to their cognitive profile [1,2].

Depending on a number of factors, the cognitive profiles of students with hearing loss may vary, requiring an individual approach to educational needs in order to achieve learning objectives [2].

For individuals with monaural cochlear implants and binaural hearing aids, the perception and processing of textual learning material may differ due to varying experiences with hearing aids and sound lateralization [3].

Text-based learning materials are one of the main ways of conveying educational information in higher education programs and therefore need to be adapted to take into account the specific difficulties that students with different types of hearing aids are likely to encounter.

In view of the above, the following research hypothesis was formulated: students with different types of hearing aids (monaural cochlear implants and binaural hearing aids) have different indicators of gaze microdynamics when reading written texts.

The aim of the study was to identify significant indicators of gaze microdynamics during the reading of written texts by students with different types of hearing aids.

Existing research confirms the need to study cognitive processes in order to develop effective learning strategies [4,5]. In this case, eye-tracking studies become sources of objective indicators of written information perception parameters for identifying universal and individual solutions and methodological practices in the educational process [6], taking into account the specific nature of reading among students with hearing impairments in general and with different types of hearing aids in particular [7].

The development of methods and materials for students with hearing impairments who use different types of hearing aids requires a detailed study of the nature of perception and the accompanying cognitive load in the process of reading written texts. It is possible to use indicators of gaze microdynamics [8], recorded using eye-tracking technology, as an indicator of these characteristics.

2. Materials and Methods

During the study, a survey was conducted among 75 students of bachelor's degree programs in engineering, studying under adapted educational programs (for students with disabilities), containing questions about the degree of hearing loss, type of hearing aid, age of the first hearing aid use, and the presence of ophthalmological disorders.

The survey results revealed the following students with hearing impairments:

- 2 students with binaural cochlear implants,
- 3 students with binaural cochlear implant and hearing aid,
- 5 students with monaural hearing aids,
- 16 students with monaural cochlear implant,
- 49 students with binaural hearing aids.

For further research using an eye-tracker, students from two large groups were selected. Among the 16 students with monaural cochlear implants, 2 students were not suitable due to visual characteristics that distorted eye-tracking and reading fixation. Among the 49 students with binaural hearing aids, 14 students were selected who were comparable in terms of hearing loss, course, age, gender, and entrance exam scores to students with monaural cochlear implants.

Ultimately, students aged 18-28 from a technical university participated in the study using an eye-tracker. They were divided into three independent groups matched for age, gender, course of study, degree of hearing loss (except for the group without hearing impairment) and entrance exam scores: a group with monaural cochlear hearing aids — 14 students; a group with binaural hearing aids — 14 students; a group of students without hearing impairments — 13 students.

The group of students with one cochlear implant consisted of two first-year students, ten middle-year students, and two graduates, among whom eleven participants were deaf in both ears, one had a fourth-degree loss in both ears, and two had a fourth-degree loss in the left ear and deafness in the right ear.

The group of students with two hearing aids consisted of three first-year students, nine mid-year students, and two graduates, including eleven participants with deafness in both ears, one with fourth-degree hearing loss in both ears, and two with fourth-degree hearing loss in the left ear and deafness in the right ear.

The group of students without hearing impairments consisted of two first-year students, nine middle-year students, and two graduates.

The exclusion criteria for participants included ophthalmological or neurological conditions that affected the quality of the recording, making it impossible to correctly register the gaze (including those manifested in the inability to pass calibration/verification) [9]. The presence of combined (multiple) developmental disorders affecting cognitive text processing strategies was also considered critical [10].

The Gazepoint GP3 (GP3SD v2) device was selected as the gaze recording equipment — a compact infrared eye-tracker with an open API. Key characteristics: sampling frequency 60 Hz, accuracy 0.5–1°; permissible head displacement ±15 cm in depth, 25 cm horizontally and 11 cm vertically [11]. A 23-inch monitor with a resolution of 1920 x 1080 pixels was used to display text,

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ensuring uniform lighting for all participants, sufficient for comfortable reading, and excluding infrared and/or pulsating light sources [12].

To accompany the instructions, the Google Live Transcribe automatic speech recognition module was used [13] with parallel text output to a separate screen. This approach ensured the necessary level of quality in the provision of instructions [14] and provided visual support for students with hearing impairments [15].

The stimulus material was selected taking into account the fact that reading and comprehension strategies depend significantly on the type of text. Narrative and expository texts were distinguished [16]. Existing studies also reveal the characteristics of cognitive work depending on whether the text belongs to one of these types [17], including in individuals with hearing impairments [18].

Two texts in Russian were used as stimuli: a narrative everyday text and a expository educational text.

The narrative everyday text shown in Figure S1 contained 76 words and was an excerpt from the news channel of the Department of Inclusive Education about a past event.

The expository educational text shown in Figure S2 contained 153 words, one system of equations, five formulas, and was an excerpt from educational materials on the subject of "Analytical Geometry".

The texts were adapted for the screen so that they occupied the entire available reading area: the lines were aligned in width, and Times New Roman font was used, as it is the most common font in technical and scientific circles. The font size and line spacing were increased to ensure that the screen was completely filled. For everyday text, the font size was 18 pt; double line spacing was chosen, which not only allowed the entire monitor to be filled with text, but also simplified the binding of gaze points (and corresponding characteristics) to the word layout for future research, thereby ensuring greater accuracy of binding in the context of the upcoming more in-depth analysis. For educational text, the font size was 14 pt; the line spacing was double for the same reasons of mapping. In addition, this contributed to the correct registration of the text scanning path by the test subjects, comfortable perception [19] and ease of working with the text for users of glasses. The line consisted of 60 characters [20].

The research procedure included the following stages:

1. Introductory message. A brief theoretical justification of the research objective and its significance for the development of adaptive educational technologies were displayed on the screen. For participants with hearing impairments, the text was accompanied by sign language interpretation and automatic speech recognition [15].

2. Personal instruction. The experimenter individually explained how to use the eye-tracker [9]; speech was automatically transcribed by Google Live Transcribe and displayed on an auxiliary screen.

3. Calibration. Standard 9-point calibration sequence [21].

4. Verification. A four-point verification grid with a permissible deviation of <1.5°. If the threshold was exceeded, recalibration was performed [21].

5. Text reading. The participant read the presented text at a comfortable pace to themselves, excluding the influence of vocalization on the microdynamics of gaze [8,22,23].

The participants read the text in the "Conducting an experiment" mode of the Neurobureau software [24,25]. The "Experiment Analysis" mode allowed us to export data with the characteristics of the students' gaze, namely: time stamps of measurement points (at a frequency of 60 Hz), screen coordinates of the gaze, and pupil diameter [21]. This primary information was further processed using methods proposed by the software developer [25], with the calculation of key indicators of visual behavior associated with cognitive load [8,9,21,25].

The I-Velocity Threshold (I-VT) algorithm, recommended for reading continuous text, was used to mark events [9,25]. Instantaneous angular velocity was calculated based on frame-by-frame increments in the direction of gaze on the screen. The velocity threshold for saccade classification was

70°/s; continuous sequences of samples with a velocity below the threshold and a duration of ≥60 ms were marked as fixations [9,25].

Also, as part of the processing algorithm, neighboring fixations were combined at an inter-fixation interval ≤60 ms and an angular distance between centers ≤0.5°, which reduces the artificial fragmentation of long gaze stops (recommendations by Holmqvist et al.) [9].

The temporal boundaries of reading were determined manually in order to exclude from the analysis both eye movements preceding reading (before the first fixation on the first word of the first line) and those related to re-reading (after fixation on the last word of the last line). Thus, the indicators reflected the initial reading of the presentation, without subsequent arbitrary re-readings [9].

Segments marked by the software as blink/lost were excluded from the analysis; interpolation of gaps was not applied. Calibration repetitions were performed at verification >1.5° to minimize systematic error [21].

The threshold of 70°/s and minimum fixation of 60 ms are compatible with a frequency of 60 Hz and are within the range recommended for reading continuous text [9]; The fusion criteria of ≤60 ms and ≤0.5° correspond to typical recommendations for smoothing fixation clusters with an accuracy of 0.5–1° [9]; the choice of I-VT and lexical AOI labelling is consistent with the practices described in works on applied eye-tracking in reading studies using Russian language material [25], as well as with the guidelines and capabilities of the Neurobureau software package [21,24].

Pupil diameter data also was preprocessed with basic guideline to provide insights on cognitive processes during reading [26]. Data points marked by eye-tracking system with low validity score were excluded as well as data points with too high dilation speed. For determining the later ones robust filter was used based on MAD value [Preprocessing pupil size data: Guidelines and code]. The resulting data points array was completed with interpolated ones in missing segments and were smoothed with low frequency filter for analyzing pupil dynamics.

In order to detect the stable component of the pupillary response (tonic pupil diameter) [27], the baseline-correction was performed.

Thus, setting the baseline pupil diameter allowed us to exclude from the analysis the data of the initial physiological reaction of pupil to the change in perceived stimuli (the transition from calibration to reading texts). It also made possible to compare records between participants without influence of personal physiological parameters [28]

The baseline pupil diameter was calculated as the average pupil dilation in the time interval from 250 to 500 ms at the beginning of reading. The start of this baseline interval for each entry was selected at point of the most pupil constriction after the text appearing on the screen, which may be considered as indicator of the adaptation of the pupils to the presented stimulus after calibration, i.e. after the stimulus changed. The interval continued as long as pupil diameter remained relatively stable [29] but ended immediately before the onset of dilation associated with cognitive processing in the reading process [30].

In the process of analyzing obtained pupil data markers of cognitive load were of particular interest. Thus, data processing had additional step of calculating points of the maximal and minimal diameter, that were taken as these markers. It was taken into consideration that selected maximum should take place after baseline interval as there it more likely corresponds with cognitive processing as it was mentioned before. The last 10% of the total text was not taken into account while searching this maximum for similar reasons, since before the end of reading, an increase in diameter could be registered, which most likely indicated general excitement associated with the completion of reading and not cognitive load [30]. After this a point of minimum was found with idea it to take place after the maximum one as decreasing pupil diameter trajectory determines lowering of cognitive load [30].

Thus, the analysis of gaze microdynamics was carried out using various variations of fixation, saccade, and pupil indicators capable of revealing the peculiarities of text information perception in the process of reading texts (everyday and educational).

The main indicators of eye-tracking results considered in this study are:

- number of fixations – the number of fixations recorded,
- total fixation time (seconds) – the total time of all recorded fixations,
- average fixation duration (seconds) – the average time of a single fixation, obtained by dividing the total fixation time by the number of fixations,
- number of saccades – the number of recorded saccades,
- total scan path length (angular degrees) – the total distance travelled by the gaze between fixation points.
- average saccade length (angular degrees) – the average distance travelled by the gaze within a single saccade, obtained by dividing the total scan path by the number of saccades,
- reading time – the total time spent reading the text,
- pupil diameter (delta from baseline in millimeters) – pupil diameter recorded during reading, specified as delta from the selected baseline value in millimeters,
- pupil diameter (delta from baseline in percent) – pupil diameter recorded during reading, indicated as delta from the selected baseline value in percent,
- part of text read (percent) – the proportion of the total reading time up to the moment of recording a particular pupil diameter value,
- time from reading start (seconds) – the time interval from the start of reading to the moment of registration of a particular pupil diameter value.

3. Results

The raw data on gaze points and pupil diameters used in this article are provided in Table S1, Table S2 and Table S3 of the supplementary materials for group without hearing impairment, group with binaural hearing aids and group with monaural cochlear implants respectively. The processed data on gaze points and pupil diameters are provided in Table S4.

3.1. Analysis of the comparison of the results of eye-tracking indicators for reading texts by groups with monaural cochlear and binaural hearing aids

Analysis of the results obtained using the Mann-Whitney criterion revealed statistically significant differences in reading indicators both between groups with and without hearing impairments and between subgroups with hearing impairments by type of hearing aid, confirming the presence of distinctive features of perception in these subgroups not only of educational material but also of everyday vocabulary in the reading process. The data are shown in Table 1.

Table 1. Eye-tracking indicators when reading different types of text (M ± SD) by students with different types of hearing aids.

Indicator	p	Group with monaural cochlear implants	Group with binaural hearing aids
Narrative everyday text			
Total fixation time (seconds)	0.062	28.35	20.98±6.54
Average fixation duration (seconds)	0.024	0.22±0.03	0.18±0.04
Number of fixations	0.306	128.57±30.99	113.93±24.22
Number of saccades	0.306	128.14±30.67	113.71±24.11
Total scan path length (angular degrees)	0.427	556.49±134.04	544.78±177.05
Average saccade length (angular degrees)	0.734	4.44±0.90	4.88±1.49
Expository educational texts			
Total fixation time (seconds)	0.077	56.81±15.73	43.31±22.05
Average fixation duration (seconds)	0.839	0.23±0.03	0.3±0.29
Number of fixations	0.024	254.29±83.57	176.5±81.41
Number of saccades	0.024	254.07±83.28	176.14±81.46
Total scan path length (angular degrees)	0.002	834.70±361.50	460.9±255.46

Average saccade length (angular degrees)	0.125	3.28±0.96	2.78±1.09
Reading time elapsed from registering the maximal pupil diameter to the minimal one (seconds)	0.039	41.15±19.42	26.64±16.85

The results obtained and analyzed based on the average fixation duration (p = 0.024) indicate a difference in the processing of everyday information in narrative text among students with monaural cochlear implants, manifested by longer delays in the perception of lexemes on average with statistically non-significant reading times.

The statistical significance of the reading time indicator recorded between the maximum pupil diameter and its minimum value (p = 0.039) during reading indicates increased cognitive load in students with monaural cochlear implants when perceiving textual educational information compared to the group of students with binaural hearing aids, as pupil constriction occurs more slowly when performing complex tasks [27]. This conclusion is supported by the fact that students with monaural cochlear implants work more intensively with the words of the educational text: a greater number of saccades (p = 0.024) and fixations (p = 0.024) reflect the increased load and complexity of lexical-semantic processing [8,9,21,25] ; an increase in the scan path length (p = 0.002) could only have occurred due to returns to already read text when working with the same text [21,25] , i.e. there were regressive saccades – the longer the total scanning path, the more regressive saccades there were, and the longer they were. This behavior indicates additional verification and integration of the word into the context of the sentence, allowing for partial compensation for the difficulties of information processing [25]. The above-mentioned students paused significantly more often on words, read them more slowly, and returned to the text to reread important information. Thus, we can say that these students have a greater need for contextual cues compared to students with binaural prostheses [8,25].

Summarizing the comparison of the results of the two groups of students with different types of hearing aids, we can speak of a statistically confirmed difference in visual behavior and perception load in the context of working with written educational texts (in terms of cognitive load).

The identified differences and peculiarities of information perception in the reading process indicate the need to take them into account in the process of preparing and designing educational materials not only for the category of students with hearing impairments, but also for subcategories that differ in the type of hearing aid.

3.2. Analysis Comparing the Results of Eye-Tracking Readings of Texts by Groups with Monaural Cochlear Implants and Without Hearing Impairments

Analysis of the results using the Mann–Whitney criterion (Table 2) revealed statistically significant differences in the indicators of reading everyday and educational texts between the groups, allowing us to gain a better understanding of the reading characteristics of students with monaural cochlear implants.

Table 2. Eye-tracking indicators when reading different types of text (M ± SD) by students with monaural cochlear implants and without hearing impairments.

Indicator	**p**	**Group with monaural cochlear implants**	**Group with binaural hearing aids**
Narrative everyday text			
Total fixation time (seconds)	0.012	28.35	19.06±7.25
Average fixation duration (seconds)	0.011	0.22±0.03	0.18±0.03
Number of fixations	0.031	128.57±30.99	103.43±25.75
Number of saccades	0.027	128.14±30.67	103.14±25.86
Total scan path length (angular degrees)	0.114	556.49±134.04	472.38±102.19

Average saccade length (angular degrees)	0.482	4.44±0.90	4.78±1.31
Reading time	0.029	34.34±11.01	25±7.6
Minimum pupil diameter registered after maximum pupil diameter (delta from baseline in millimeters)	0.01	-0.63±0.3	-0.3±0.35
Minimum pupil diameter registered after maximum pupil diameter (delta from baseline in percent)	0.003	-16.24±8.15	-6.98±7.97
Time elapsed from maximum to minimum pupil diameter (seconds)	0.006	28.15±11.09	17.63±6.15
Reading time elapsed from registering the maximal pupil diameter to the minimal one (seconds)	0.029	19.82±8.99	12.67±6.77
Expository educational texts			
Total fixation time (seconds)	0.227	56.81±15.73	50.9±25.76
Average fixation duration (seconds)	0.701	0.23±0.03	0.35±0.33
Number of fixations	0.044	254.29±83.57	187.5±79.98
Number of saccades	0.044	254.07 ±83.28	187.29±80.02
Total scan path length (angular degrees)	0.009	834.70±361.50	489.8±179.83
Average saccade length (angular degrees)	0.265	3.28±0.96	2.91±1.1
Part of text read before registered minimum pupil diameter (percentage)	0.038	68.94±21.75	84.19±11.24

A comparison of statistically significant results of the parameters of the process of reading everyday text by students with monaural cochlear implants reveals a general tendency to work intensively with words due to an increased number of saccades (p = 0.027) and fixations (p = 0.031), which in turn reflects an increased cognitive load in the reading process and lexical-semantic difficulties in processing the material [8,9,21,25]. In addition to the above features, reading everyday narrative information is characterized by a longer processing time for everyday text as a whole, in accordance with the level of significance of the text reading time indicator (p = 0.029), and individual lexemes of the text, in accordance with the indicators of average (p = 0.011) and total fixation time (p = 0.012).

Analysis of significant pupil diameter indicators when reading everyday text allows conclusions to be drawn about the increased cognitive load experienced by students with monaural cochlear implants compared to students without hearing impairments, as evidenced by a narrower pupil diameter in millimeters (p = 0.011) and as a percentage (p = 0.011) of the baseline and their slow constriction (p = 0.006) with longer reading times during which constriction occurred (p = 0.029) with prolonged pupil constriction times (p = 0.006) [31,32] , [27].

A comparison of statistically significant results of the parameters of the process of reading educational texts reveals a general tendency towards intensive work with words due to an increased number of saccades (p = 0.044) and fixations (p = 0.044), which in turn reflects an increased cognitive load in the reading process and lexical-semantic difficulties in processing the material [8,9,21,25]. In addition, when reading educational texts, there are additional differences in the number of returns to the read text in terms of the total scan path length (p = 0.009). The described indicator of returns with a smaller volume of text read before reaching the minimum pupil diameter (p = 0.038) suggests that students with monaural cochlear implants experienced increased cognitive load when perceiving written educational information earlier than the group of hearing students [8,21,25].

Based on the results of comparing the reading performance of different texts by the above-mentioned groups, it can be recommended that when selecting educational materials for students with monaural cochlear implants, reference inserts should be used to minimize backtracking and, consequently, avoid the load associated with text orientation.

3.3. Analysis of the Comparison of the Results of Eye-Tracking Indicators for Reading Texts by Groups with Binaural Hearing Aids and Without Hearing Impairments

Analysis of the results using the Mann–Whitney criterion (Table 3) revealed statistically significant differences between the groups only when reading educational texts.

Table 3. Eye-tracking indicators when reading different types of text (M ± SD).

Indicator	p	Group with monaural cochlear implants	Group with binaural hearing aids
Narrative everyday text			
Total fixation time (seconds)	0.329	20.98	19.06±7.25
Average fixation duration (seconds)	0.964	0.18±0.04	0.18±0.03
Number of fixations	0.150	113.93±24.22	103.43±25.75
Number of saccades	0.164	113.71±24.11	103.14±25.86
Total scan path length (angular degrees)	0.511	544.78±177.05	472.38±102.19
Average saccade length (angular degrees)	0.511	4.88±1.49	4.78±1.31
Expository educational texts			
Total fixation time (seconds)	0.571	43.31±22.05	50.9±25.76
Average fixation duration (seconds)	0.541	0.3±0.29	0.35±0.33
Number of fixations	0.701	176.5±81.41	187.5±79.98
Number of saccades	0.701	176.14±81.46	187.29±80.02
Total scan path length (angular degrees)	0.603	460.9±255.46	489.8±179.83
Average saccade length (angular degrees)	0.701	2.78±1.09	2.91±1.1
Text part read from the moment of maximum pupil diameter to the moment of minimum pupil diameter (percentage)	0.008	49.27±23	71.11±11.57
Reading time elapsed from registering the maximal pupil diameter to the minimal one (seconds)	0.012	26.64±16.85	44.41±19.35

No statistical significance was found in the reading indicators of everyday narrative text in students with binaural hearing aids, which suggests that they have sufficiently developed compensatory functions for perceiving written everyday information.

However, when reading educational texts, students with binaural hearing aids showed statistically significant indicators of increased cognitive load compared to the group of students without hearing impairments.

We see that students with binaural hearing aids reached the minimum pupil size (p = 0.008) at an earlier stage of reading with equal reading duration (judging by the lack of statistical significance of this indicator), which means that they experienced cognitive load faster, as further confirmed by the time of registration of the minimum pupil diameter in seconds of reading the text (p = 0.012).

The load was revealed by the indicator of shorter reading time before pupil constriction [31,32], while the pupil diameter did not differ, and there was no additional work with terminological vocabulary and contextual orientation, which allows us to conclude that the perception of written educational text is more labor-intensive.

3.4. General Conclusions on the Reading of Different Types of Text by Students from Different Groups

Based on the data obtained and processed, we can talk about statistically significant differences in visual behavior and cognitive load [8,25] in the process of reading texts by students with different types of hearing aids. In particular, the reading results of students with binaural hearing aids indicate more developed compensatory abilities to overcome difficulties in perceiving not only educational but also everyday information in written form.

The results presented in Tables 1, 2, and 3 provide insight into strategies for working with everyday and academic written texts in the reading process, not only for individuals with hearing impairments, but also for those with different types of hearing aids. In particular, the results of students with binaural hearing aids are close to those of students without hearing impairment in terms of the number of fixations and saccades when perceiving everyday information in written form, while students with monaural cochlear implants show a statistically significant difference in these indicators.

Thus, we suggest that binaural hearing aids contribute to a reduction in cognitive load when perceiving everyday information in written form, and we confirm the assumption about differences in the cognitive profiles of students with different types of hearing aids.

4. Discussion

The results obtained in the study confirm the hypothesis of significant differences in information perception depending on the type of hearing aid in the context of cognitive load when reading written texts. In this section, we will discuss the results obtained, their consistency with existing theories, and directions for further research.

Based on the results obtained, we see a need not only to adapt written teaching materials, but also to form study groups of students with hearing impairments according to the type of hearing aid they use within the framework of inclusive education. Such a measure will allow for the individualization of the educational process, enabling groups of students to be provided with the necessary sets of special technical teaching aids and adapted teaching materials without excess or deficiency, adapting the educational process to the pace of perception, form of presentation, and other individual needs of students.

The identified differences in results between groups with different types of hearing aids in terms of reading time and reading load are consistent with the cognitive load model (Sweller, 1988) [33]. Binaural hearing aids, by providing interhemispheric asymmetry in the perception of sound information [34], can reduce the cognitive load associated with compensating for hearing loss, freeing up resources for text processing. This explains the shorter fixation duration and reduced number of regressions, reflected in the total scanning path length parameter, in students with binaural hearing aids.

Binaural hearing aids stimulate symmetrical activation of the temporal lobes during auditory perception, improving the processing and memorization of acoustic and semantic images of words, which subsequently influences their recognition when reading written text, facilitating work with written materials. [35]. This is confirmed by a lower number of fixations compared to the group of students with monaural cochlear implants, highlighting the importance of binaural hearing aids [3] for accelerating the processing of everyday information in the process of solving everyday tasks.

The observed stability of indicators when the text (educational materials) becomes more complex is consistent with the dual coding theory (Paivio, 1986) [36]. Binaural processing probably enhances the interaction between verbal and visual subsystems, which is especially important when perceiving syntactically complex constructions.

The effectiveness of the proposed adaptations certainly requires verification and research with larger sample sizes. Particular attention should be paid to the influence of monaural and binaural hearing aids on the process of reading texts that vary in length, complexity, and genre.

5. Conclusions

The results obtained indicate a systematically higher cognitive load when reading among students with hearing impairments compared to students without hearing impairments. At the same time, students with binaural hearing aids cope with reading educational and everyday text materials with less time and difficulty in working with vocabulary, according to an analysis of saccade and indicators of the overall text scanning path, compared to the group of students with monaural hearing aids.

Based on the results obtained, we have formulated proposals for adapting written educational materials for these groups.

Firstly, it is necessary to introduce key vocabulary in advance (glossaries on the topic, highlighting of terms, brief definitions before the text): this reduces the complexity of initial lexeme recognition and decreases the average duration of fixations on words that carry meaning [37,38]. Secondly, visual aids for contextual orientation (structural subheadings, marked lists, section "road signs", graphic markers of connections) are useful because they simplify the return to places in the text that require rethinking, facilitating the integration of what has been read into the macrocontext [39,40].

In practice, this means that special didactic solutions and regulations for the design of teaching materials are needed: preliminary introduction of key vocabulary to simplify its recognition and visual aids for better orientation in the context of the material.

Despite the limitations, the study demonstrates that binaural hearing aids, compared to monaural ones, have significant differences in the process of reading written texts, presumably due to greater optimization of audiovisual integration and reduced cognitive load. These data justify the need to expand the practice of binaural hearing aids and develop specialized support techniques for people with monaural hearing aids, especially in educational contexts.

Supplementary Materials: The following supporting information can be downloaded at the website of this paper posted on Preprints.org, Figure S1: Image with the narrative everyday text and its English translation; Figure S2: Image with expository educational text and its English translation; Table S1: The raw data on gaze points and pupil diameters for group without hearing impairment; Table S2: The raw data on gaze points and pupil diameters for group with binaural hearing aids; Table S3: The raw data on gaze points and pupil diameters for group with monaural cochlear implants; Table S4: The processed data on gaze points and pupil diameters for all groups. The following supporting information can be downloaded at the website of this paper posted on Preprints.org

Author Contributions: Conceptualization, R.F. and M.K.; methodology, R.F. and I.P.; software, I.P.; validation, I.P. and R.F.; investigation, R.F., I.P. and M.K.; data curation, R.F. and I.P.; writing — original draft preparation, R.F. and I.P.; writing—review and editing, M.M.; supervision, M.K.; project administration, M.K. All the authors have reviewed the published version of the manuscript and agreed with it.

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