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The Specifics of Oculomotor Activity in Children With Hearing Impairment in the Independent and Joint Performance Process of a Training Task With an Adult

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Abstract: **Introduction**. The transitional status of a sample of children with hearing impairment after cochlear implantation expands the possibilities of studying the consequences of violations of individual sensory systems affecting the joint attention deficit. The method of registering eye movement has advantages in studying the difficulties of learning processes in children with hearing impairment. The novelty of the study lies in the synchronous tracking of eye movements with superimposed gaze paths of two experimental participants (an adult and a child with hearing impairment) in a learning situation and the use of a time marker of simultaneous fixations as an indicator of joint attention. Based on the data of oculomotor activity during the independent and synchronous performance of an educational task with an adult, the specifics of visual attention that hinder the learning of children with hearing impairment can be identified. **Methods**. Study sample: 16 preschoolers with hearing impairment (sensorineural hearing loss, class H90 according to ICD-11) and 16 typically developing children. Experimental situations of independent and synchronous performance of an educational task with an adult are involved. The leading method was to register eye movement with a portable PLabs eye tracker. **Results**. When performing a task synchronously with an adult in oculomotor activity in children with hearing impairment, the number of fixations indicating constant joint attention increases (from 300 milliseconds), there is greater relevance of fixations and an increase in the duration of maintaining visual attention to educational samples, as a result, a decrease in errors. Compared to typically developing children, the speed of information processing and the allocation of targeted stimuli changes in children with hearing impairment. **Discussion**. In episodes of joint attention in a learning situation, the synchronicity of interaction between a child with hearing impairment and an adult is achieved through fixations lasting from 300–500 and above 500 milliseconds (ms). However, the ability to maintain this joint attention in children with hearing impairment is less than in typically developing peers.

Keywords: joint attention, divided attention, education, lifespan development, preschool age, anormogenesis, hearing impairment, cochlear implantation, oculography, eye tracker

Highlights:

➢ The primary token of learning difficulties in children with hearing impairment is the change in fixation time.
➢ Unlike typically developing children, the speed of information processing changes in children with hearing impairment.
➢ The main difficulties hindering the learning process of children with hearing impairment are highlighted: changes in the time of fixation, low duration of maintaining visual attention and joint attention, changes in the number and duration of targeted fixations.
➢ The special aspects of the organization of the perceptual action with varying degrees of compatibility/independence of task performance are analyzed; when performing tasks synchronously with an adult, children with hearing impairment had a greater relevance of fixations and an increase in the duration of joint attention, the time spent on the allocation of target stimuli decreased.

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Introduction

In modern science, the most relevant is the study of the atypical development of children through a deficit of socio-cognitive skills, namely, a deficiency of joint attention that hinders a child's comprehensive development and learning.

Joint attention is a cognitive process that is based on the mechanism of extrapolation of another person's line of sight (constructed along an imaginary line in space in accordance with the orientation of the interlocutor's head and eyes) in order to identify an object or event that has come into the focus of his attention (Franco & Butterworth, 1996). Such realization of joint attention requires making assumptions about the other person's intentions. This definition of shared attention leads to the understanding that when someone looks in a concrete direction, it should influence where the other person focuses their attention (that means we should keep track of where others are looking). At the same time, the other person's head and eyes positions are an insufficient source of information about the object of his attention. People generate multimodal behavior and their attention and interest in an object, potentially signaling to others through a variety of modalities, including interaction with the object itself, gestures, speech, and talking about objects (Bakeman & Adamson, 1984; Yu & Smith, 2017b; Yu & Smith, 2017a; Schroer & Yu, 2021). This mutual awareness is crucial in the learning process (for example, to focus on the learning material).

Many studies of the age-related development of joint attention focus on normative patterns and on the occurrence of joint attention deficit. Individual differences in joint attention skills in children are associated with subsequent speech and cognitive development (Adamson et al., 2019; Delgado et al., 2002; Mundy, 2018; Smith & Ulvund, 2003; Brooks & Meltzoff, 2005), the development of intellectual abilities and IQ (Mundy, 2018; Redcay et al., 2012), the effectiveness of learning processes (Dawson et al., 2004; Nichols et al., 2005), social competence (Van Hecke et al., 2007), self-regulation (Morales et al., 2005).

Researchers have successfully adapted the paradigm of joint attention for clinical cases, for example, autism (Johnson & Johnson, 2005; Ristic et al., 2005; Vlamings et al., 2005); it has been shown that atypical joint attention often comes with cognitive and affective deficits found in schizophrenia (Dalmaso et al., 2013), Turner syndrome (Campbell et al., 2002), attention deficit hyperactivity disorder (Marotta et al., 2018; Langdon et al., 2006), Williams syndrome (Marotta et al., 2018).

Few studies have been devoted to a detailed examination of primary disorders that can lead to a deficit of joint attention, directly resulting from the biological nature of pathologies (such as auditory analyzer). For this scientific task, it is significant to use a sample of children with disorders in the auditory analyzer system. It will be possible to trace the potential mechanisms underlying the atypical joint attention that prevents effective learning, using the example of the consequences of hearing impairment.

Previous studies have shown a variety of pathways leading to coordinated attention of hearing-impaired children and adults, suggesting flexibility and reliability in using multiple options to achieve the same functional goal of interaction (Chen et al., 2020). For the deaf and hard of hearing, for the purpose of communication, the following are most often used: a) gestures, in combination with b) facial expressions, c) the shape or movement of the mouth and lips, as well as in combination with d) the position of the body core. These sets special unique multimodal means of establishing joint attention. Limited sensory experiences with hearing loss affect attention coordination between children and adults (Chen et al., 2019, 2020, 2021). Hearing loss was shown to not affect the probability that parents and children addressed the same object at the same time during the game. However, following the attention of parents, children with hearing loss used both the direction of the parents' gaze and hand movements as signals, while typically developing children relied mainly on the actions of their parents. In previous studies, changes in the means of establishing joint attention are recorded.

It is important to emphasize that the deficit of joint attention in children with hearing impairment may be associated with the peculiarity of their use of means of establishing episodes of joint attention, the nature and degree of their communication with adults (Peterson & Slaughter, 2003), communication modality preferences and approaches to the education of a child with hearing impairment in the family (Dunn & Brophy, 2005), the presence of sensorimotor exchange and pre-linguistic communication between a child and an adult (Meins et al., 2002).

Thus, the parenting style contributes to the various patterns of joint attention of children with hearing impairment. Studies also indicate that mothers of deaf children use higher levels of directive parenting style, which leads to less success in speech development (Musselman & Churchill, 1992). The maternal directive is described as a tendency to prompt, prevent, or prohibit certain behaviors, elicit reactions, and control the course and topics of conversation. Verbal imperatives, such as non-verbal control behavior (for example, removing toys), were observed more frequently in mother-child dyads with hearing impairment. Mothers could use controls in attempts to control auditory and visual attention (Meadow-Eagles, 1997). Hearing parents of deaf babies tend to be more directive, less responsive, less flexible, less consistent, and use plainer language than mothers from all other dyads (e.g., Chen et al., 2019; Fagan et al., 2014; Meadow-Orlans, 1997).

Other studies show that mothers of children with hearing impairment are overly responsive in communicating with them compared to those mothers whose children hear, this is described as a “nonvariative response to the demand for attention”. They are about six times more likely to be ready to respond to the child’s demands of attention and strive to respond instantly to signals, not allowing attempts to attract attention to form sufficiently.

From the research point of view, a group of children with hearing impairment with a cochlear implant is of particular interest to us. Cochlear implantation is a complex system of measures to restore auditory sensation by electrical stimulation of the fibers of the auditory nerve, aimed at full-fledged social adaptation and mental correction of children with profound hearing loss.

After cochlear implantation, the state of the children changes. Children with a cochlear implant are able to perceive sound signals, perceive nonspeech sounds, and react to them. However, the child continues to rely on the skills and abilities formed earlier in conditions of severe hearing impairment. Visual supports and habitual means of speech perception and communication are still significant for him: lip reading, written speech, dactylology, sign language, the habit of controlling pronunciation using kinesthetic supports, etc. Until the initial stage of rehabilitation is completed, that is, until there is a restructuring of communication and interaction of the child, he retains this special (transitional) status.

However, only a few studies are devoted to the joint attention of cochlear-implanted children with hearing impairment and the ability to trace changes in the means of establishing joint attention after cochlear implantation.

The prerequisite is the previous data, which confirms that the synchronicity, complexity, and orientation in the interaction of mothers with infants change before and after cochlear implantation (Fagan et al., 2014). For example, mothers' utterances more often overlapped the vocalizations of infants with hearing loss before cochlear implantation than after it. Mothers used fewer complex ones with infants with cochlear implants compared to their hearing peers. Together, mothers and babies adapted relatively quickly to infants' access to cochlear implants. They demonstrated improved interaction synchronicity, more active use of words by infants, and levels of maternal language complexity compatible with the use of words by infants, all within seven months after activation of the cochlear implant (Fagan et al., 2014).

Although maternal control decreased over time, the changes were minimal and did not correspond to children's speech development (Musselman & Churchill, 1992). It is significant for us to confirm the changes in the way of interaction (namely, the means of establishing joint attention) and synchronicity necessary for joint attention skills development after cochlear implantation.

Thus, the study of dyadic interaction in connection with cochlear implantation will be important in establishing patterns of joint attention, which have been shown to persist over time (Meadow-Orlans, 1997). The same patterns of joint attention will manifest when teaching this group of children.

The transitional status of the sample of children with hearing impairment after cochlear implantation, in our opinion, opens up new research opportunities for considering the scientific question of the role and consequences of the violation of individual sensory systems in the formation of joint attention skills.

After cochlear implantation in the motor-sensory development process, the child learns to use auditory sensations to perceive events at a distance, pronounce speech sounds and present them to the environment, and recognize speech signs. Through phonological development, a child learns how to select, modify, and combine basic sounds and patterns of speech movements to create meaningful utterances. This specificity of correction and education of children with hearing impairment also forms specific means of establishing joint attention.

Moreover, it is noted that children with hearing and visual impairment have unsystematic inaccurate ideas about their sensory-perceptual capabilities, external signs, structure, and functional purpose of the sense organs. It does not allow a child with pathology to actively engage in the process of compensating for his defect. Only some preschoolers realize the need to use preserved sensory organs, which directly affects the specifics of joint attention skills in this group of children.

Also, the problem of access to typical social and behavioral signals about the mental state of other people is related to the fact that children's knowledge of the syntax, semantics and morphology of sign and spoken languages correlates with their indicators of the skills of initiating and responding to joint attention (de Villiers, 2005; Lohmann & Tomasello, 2003; Ruffman et al., 2003; Schick et al. al., 2007; Woolfe et al., 2002; Milligan et al., 2007).

The highlighted scientific problems show that the main problem for our study is the problem of studying the deficit of joint attention of children with hearing impairment in the learning process.

Joint attention plays a unique role in the learning process of children with hearing impairment in terms of the ability to maintain visual attention. It is due not only to the later formation of skills to use the means of organizing awareness, and managing it, including a later transition to internal means, but also to a lag in the development of speech that contributes to the organization and management of one's behavior. Arbitrary attention is mediated by the communication of the child with adults. The pointing gesture and the speech instruction of adults distinguish a concrete object from the surrounding world – all these are means of maintaining the child's joint attention. At the same time, for children with hearing impairment, these tools are modified.

The unavailability of all means of establishing joint attention and the instability of maintaining joint attention will be specific for children with hearing impairment. Under the influence of sensory deprivation and upbringing, the patterns of initiation and reaction of joint attention change and the non-variability of the response to the initiation of joint attention is formed.

In this regard, it is significant to study how, to establish joint attention with the help of safe analyzers, the orientation of a child with a violation of individual systems occurs and subsequently consolidates and develops this ability to navigate in the presented educational material, for example, a sample.

Given the difficulties in establishing joint attention, the underdevelopment of skills and means of communication, the difficulties of arbitrary organization of the child, and the instability of combining attention on one object with an adult, it is necessary to find a combination of direct, arbitrary, and indirect ways of organizing the learning and development of children with hearing impairment.

The mechanism of joint attention ensures the formation of base learning functions (reading, writing, and counting) in interaction with an adult. When learning, joint attention contributes to the processing of auditory, kinesthetic, visual, and visual-spatial information presented to adults. The attention of children with hearing impairments depends more on the expressiveness of the material than that of hearing people. In this regard, when teaching children with impaired hearing, various means of visualization are used: some – to attract involuntary attention (for example, a bright picture), others – to develop arbitrary attention (diagrams, tables). In addition, the peculiarities of the attention of children with hearing impairments are related to the fact that

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visual perception is more important to them and that the main burden of processing incoming information falls on the visual analyzer. For example, the perception of verbal speech by reading from the lips requires full concentration on the face of the person speaking, and the perception of dactyl speech is on the positions of the fingers. Children with hearing impairment rely on multisensory functioning (coordination of visual, language, and motor signals) to exchange social experiences/interests (Yu & Smith, 2017a).

The main task is to display the logic of the functioning of joint attention in the learning process in children with hearing impairment. In particular, it will be possible to identify the destruction of the processes involved in joint attention, which reduces the effectiveness of the child's learning.

The solution to this problem will allow us to identify ways, means and ways of compensating for developmental disorders in children with hearing impairment, to develop "workarounds" of learning and the organization of the educational environment in accordance with the capabilities of the child.

At the same time, previous methods of studying joint attention are based on the observation of behavioral manifestations and a rating system, and in most cases involve video recording with subsequent evaluation by experts (such as the ESCS (Early Social Communication Scales) test developed by P. Mundy). These methods do not allow fully objectively trace the accuracy of observation of a glance or object in episodes of joint attention and to identify critical points in changes in general focus within an episode of joint attention or perception of educational material.

The eye movement recording technologies development has opened up new opportunities for the study of joint attention, and eye tracking as a potential diagnostic tool is gaining popularity. Episodes of shared attention can be studied using eye movement registration paradigms, and such assessments can provide new insights into the relatively atypical development of shared attention.

At the same time, for a long time, there were no research tools to display how a child and an adult perceive the world when they act synchronously in it. With the development of eye tracking technology, it has become possible to trace the transformation of a child's perceptual processes more objectively under the influence of learning (Shvarts, 2018; Chen et al., 2021).

The eye movement analysis method has been used to study the learning process, for example, in several studies related to children's perception of visual materials in the learning process. It was studied which of its characteristics contribute to improving understanding and comprehension of the material and how the child's perception is reconstructed under the influence of learning (Abrahamson & Sánchez-García, 2016; Duijzer et al., 2017).

The method of tracking the direction of gaze in comparison with other methods will improve the measurement of less accessible markers of violation of joint attention, including a detailed analysis of the routes and time of fixing the gaze on the training goal, which will allow you to identify what allows you to maintain joint attention to an object or event in the learning process.

The dynamics of gaze in the learning process is crucial for establishing episodes of joint attention and it is the method of tracking eye movement that makes it possible to fix it.

The novelty lies in the fact that in previous studies spatial coordination (fixation in a specific area of interest) was often used as a criterion (Richardson et al, 2007; Shvarts, 2018) in other studies they looked for evidence that the child knew about the direction of adult attention only on the basis that the child looked into the partner's face for coordinated visual attention to the same object (Baron-Cohen & Cross, 1992; Brooks & Meltzoff, 2005; Mundy et al., 2007). However, the fact that a child does not look at an adult's face does not mean that a child is unaware of the direction of an adult's attention. That is, not only spatial characteristics (zones of interest) are important for establishing episodes of joint attention, but also the characteristics of fixation time (Shvarts, 2018; Yu & Smith, 2017a).

Therefore, in our opinion, it is necessary to use not only the spatial characteristics of fixation (determinants of stimuli on which fixation occurs), but also a more objective measure. It is a degree to which an adult and a child directed their gaze at the same object at the same time, and how long this fixation lasted. As some studies show, this criterion is more suitable for the analysis of the natural conditions of interaction (Yu & Smith, 2017a).

Moreover, in our opinion, it is required to analyze two main categories of gaze fixation durations: short glances, less than 300 ms (the threshold for sustained attention used in previous studies) (Yu & Smith, 2017b; Ruff & Lawson, 1990), long gazes, lasting from 300 to 500 ms. The second category is generally considered to be permanent attention. Additionally, it is planned to use gaze fixations of 300 ms or longer, associated with joint attention or moments when an adult also looked at a selected area.

That is, *the primary purpose* is to identify, using the eye movement tracking method, the features of oculomotor activity of children with hearing impairment in the independent and synchronous with an adult performance of a learning task, which can reliably predict learning difficulties associated with a lack of joint attention.

Methods

Experimental situations were created based on a child's learning.

In *the first phase* of the experiment, a visual sample with a pattern was placed in front of a child. A child had to draw exactly the same pattern according to the visual sample. During the instruction, an adult experimenter explained the task of drawing exactly the same pattern. The phase assumed the independent implementation of the action program by a child.

In *the second phase* of the experiment, a child was given verbal instructions for a graphic dictation: they had to draw a pattern without a visual sample. The task was performed only according to the verbal instructions of an adult. In the second phase, a child performed an action following only verbal instructions. That is, the phase assumed the joint synchronous execution of a program of actions and step-by-step control by an adult. Planning and control were shared between an adult and a child. The child was given the instruction: "Now we will draw a pattern. You must listen to me carefully. I will say how many cells and in which direction you should draw a line. Only the line that I will say is being drawn. The next line must be started where the previous one ends, without lifting the pencil from the paper. Are you ready? We begin to draw the first pattern. Put the pencil on the highest point. Draw a line: one cell down. We do not take the pencil off the paper. Now one cell to the right", and so on.

In our opinion, it is in the second phase of the experiment that intersubjective sensorimotor coordination of an adult and a child appears by anticipating and carefully tracking each other's perceptions and actions. It becomes possible to trace episodes of joint attention: an adult controls a child's perceptual activity in stages and contributes to the emergence of new sensorimotor circuits. This is where the synchronism or mismatch of perceptual systems is important to maintain joint attention in the learning process.

Additionally, as *the third phase*, the correction task was used to fill in figures (according to the "Pieron–Ruser" method). On the form that was given to a child, various blank figures are depicted,

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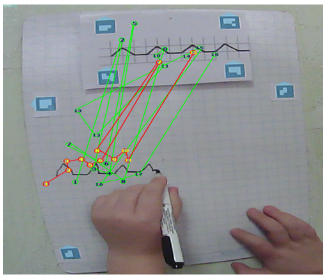
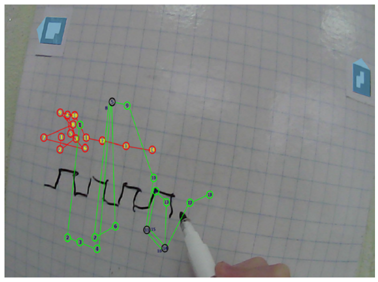
arranged in several rows. To fill in the figures, a special "key-sample" was offered separately. It is a similar set of figures, but on a separate sheet, on the example of which the rule for completing the task was explained to a child in a different form.

Figure 1

The example of processing and visualization of thermal maps of images obtained from the stage camera of the eye-tracker placed on the head of a child with hearing impairment



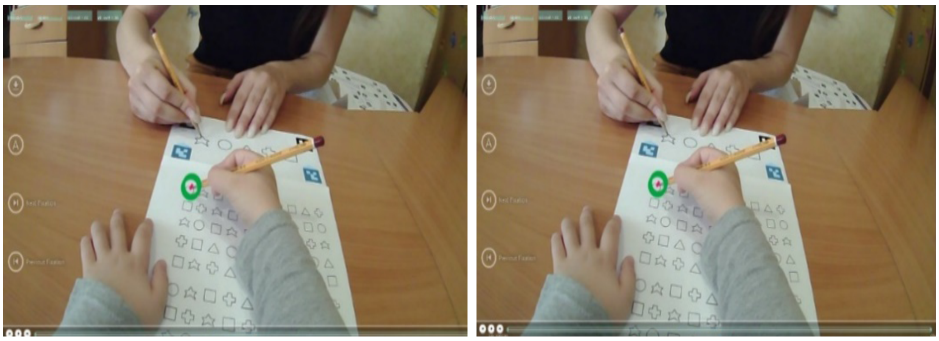
a) performance according to the sample



б) synchronous perfomance with an adult

Figure 2

The example of processing and visualization of thermal maps of images obtained from the stage camera of the eye-tracker placed on the head of a child with hearing impairment



Equipment

The main method was the method of eye movement registration using a portable tracker Pupil Headset – PLabs – an eye-tracker in the form factor of glasses, binocular version. Camera delay – 4.5 ms. Processing latency depending on a central processor > 3 ms.

The following indicators of oculomotor activity were used as the main indicators: duration of fixations, frequency of fixations, distribution of fixations, areas of interest, area of fixation. Fixations on the area on which the task was performed and on the sample with the training task were analyzed as target zones.

The most important parameters for analysis were the duration of target and non-target fixations, and the duration of the first target and non-target fixation. We analyzed fixations with a duration of less than 300 ms, in the range of 300–500 ms, longer than 500 ms. Separately, we analyzed the degree to which an adult and a child directed their gaze at the same object at the same time and how long this fixation took place. These are fixations with a duration of less than 300 ms, in the range of 300–500 ms, longer than 500 ms, fixed simultaneously with an adult.

Empirical study sample

To understand the normative and deficient manifestations of joint attention, a comparative study of a sample of typically developing children (n = 16) of preschool age with hearing impairment with cochlear implants (n = 16) was planned. It was supposed to study children with hearing impairment (sensoneural hearing loss, class H90 according to ICD-10).

Results

Using the Student's t-test, the parameters of the oculomotor activity of children with hearing impairment were compared in the 1st phase of the experiment, where they independently acted according to a visual sample after the instruction of an adult, and the 2nd phase of the experiment, where the instruction was carried out step by step synchronously with an adult (table 1).

Table 1

Comparison of oculomotor activity in 2 phases of the experiment

Oculomotor parameter	1st experiment phase	2nd experiment phase	t	Signif. (two-tailed)
Duration of fixations	17355.38 ± 1729.02	21841.96 ± 2568.91	–2.511	0.024
Duration of target fixations	12505.80 ± 1241.65	18831.64 ± 2714.97	–3.428	0.004
Duration of non-target fixations	4849.57 ± 842.55	3010.32 ± 812.94	2.685	0.017
Duration of the first target fixation	64.28 ± 2.66	100.2571 ± 11.00279	–2.861	0.012

It was found that in the 2nd phase of the experiment, when the task was performed synchronously with an adult, children with hearing impairment showed a statistically significant increase in the average duration of fixations, the duration of the first target fixation, and the time of target fixations. At the same time, the duration of non-target fixations decreased. That is, the synchronous performance of a learning action led to the fact that in children with hearing impairment, the time spent on distinguishing target stimuli becomes less, fixation on target areas becomes more stable, and non-target fixations decrease.

The comparison was made of the frequency of occurrence of fixations, indicating sustained attention – in terms of duration from 300–500 ms and longer than 500 ms (table 2).

Table 2

Comparison of oculomotor activity in 2 phases of the experiment

Oculomotor parameter	1st experiment phase	2nd experiment phase	t	Signif. (two-tailed)
Number of fixations, less than 300 ms	139.87 ± 12.78	192.87 ± 24.89	–2.710	0.016
Number of fixations, 300–500 ms	1.25 ± 0.30	2.50 ± 0.67	–2.298	0.036
Number of fixations, longer than 500 ms	0.12 ± 0.085	0.62 ± 0.17	–3.873	0.002

With simultaneous performance and guidance of an adult, in contrast to independent work with a sample, children with hearing impairment increase the number of fixations indicating constant attention (from 300 ms and longer).

The moments of the video were selected separately and the fixations of a child were selected, which occurred simultaneously with the fixations of an adult on the same stimulus material (training sample and training area) – moments of joint attention. These are not just moments of simultaneous visits to the visual area, but the synchronism of the visual attention of a child and an adult. The comparison was made of the frequency of such simultaneous fixations of an adult and a child, indicating stable attention – from 300–500 ms and longer than 500 ms (table 3).

Table 3

Comparison of oculomotor activity in 2 phases of the experiment

Oculomotor parameter	1st experiment phase	2nd experiment phase	t	Signif. (two-tailed)
Number of fixations, less than 300 ms, simultaneous with an adult	60.25 ± 7.90	122.87 ± 16.49	–4.421	0.0001
Number of fixations, 300–500 ms, simultaneous with an adult	0.50 ± 0.18	1.87 ± 0.58	–2.515	0.024
Number of fixations, longer than 500 ms, simultaneous with an adult	0.125 ± 0.085	0.62 ± 0.17	–3.873	0.002

It was revealed that in the 2nd phase, when the task was performed synchronously with an adult, at the moment of joint attention, the number of fixations increased, indicating constant attention. Moments of looking at the same target area at the same time with a fixation of 300 ms or longer were observed in both a child and an adult.

Comparison of fixations on the working field, where the child drew a pattern, shows that when working according to the instructions with an adult, a child fixes on it more often and longer (table 4).

Table 4

Comparison of oculomotor activity in 2 phases of the experiment

Oculomotor parameter	1 sample	2 sample	t	Signif. (two-tailed)
Number of fixations on the area	111.75 ± 10.56	180.50 ± 24.51	–3.534	0.003
Duration of fixations on the area	9945.58 ± 1084.94	17491.05 ± 2681.60	–3.913	0.001
Average duration of fixations on the area	86.78 ± 3.08	91.58 ± 4.32	–2.105	0.053

Further, to determine the specifics of the group of children with hearing impairment, the comparative analysis of this sample was made with a sample of typically developing children. Analysis of variance made it possible to identify significant differences in oculomotor activity during the training of two contrast groups (Levene's test > 0.05) (table 5).

Table 5

Comparison of oculomotor activity of children with hearing impairment and typically developing children

		Mean ± standard error	F	Significance
Duration of fixations	Typically developing children	27714.35 ± 5076.46	6.609	0.025
	Hearing impaired children	17355.38 ± 2531.03		
Duration of the first fixation	Typically developing children	81.19 ± 7.11	12.368	0.004
	Hearing impaired children	61.14 ± 3.60		
Duration of the first target fixation	Typically developing children	81.08 ± 7.206	7.886	0.016
	Hearing impaired children	64.28 ± 3.89		
Number of fixations shorter than 300ms	Typically developing children	229.0 ± 28.51	11.126	0.006
	Hearing impaired children	139.87 ± 18.71		

		Mean ± standard error	F	Significance
Number of all fixations	Typically developing children	270.00 ± 21.22	4.670	0.052
	Hearing impaired children	198.62 ± 23.66		
Duration of target fixations	Typically developing children	24266.70 ± 2979.79	12.608	0.004
	Hearing impaired children	12505.80 ± 1817.59		
Number of fixations on the sample	Typically developing children	63 ± 6.69	5.562	0.036
	Hearing impaired children	30 ± 10.94		
Duration of fixations on the sample	Typically developing children	5640.71 ± 512.25	6.421	0.026
	Hearing impaired children	2665.33 ± 933.99		
Duration of fixations on the area	Typically developing children	18383.83 ± 3473.37	5.822	0.033
	Hearing impaired children	9945.58 ± 1588.19		

Compared to typically developing children, children with hearing impairment have a shorter average duration of fixations, the duration of the first fixation, as well as the duration of the first target and target fixations in general. That is, there is a change in the fixation time. One can draw a conclusion that that in children with hearing impairment, attention is focused less time on target stimuli, but they need less time from the beginning of the presentation of an instruction to the start of viewing (according to the duration of the first fixation). However, the reduced duration of the first fixation on target stimuli indicates their low interest value and visibility for a child. The data reflects the difficulties of processing the target information feature, its selection.

In hearing impaired children, the number of total fixations, the number of fixations on the sample, and the duration of fixations on the sample are lower than in typically developing children. That is, according to the oculomotor activity of children with hearing impairment, the specificity of visual attention to educational material is confirmed.

Further, to answer the question of what parameters of oculomotor activity are associated with errors in the performance of the training task, regression analysis was applied. As a dependent variable, the number of all filling errors in the correction task in the third phase was chosen. The parameters of oculomotor activity were used as independent variables.

It was found that the number of mistakes made by children with hearing impairment depends on the number of fixations lasting longer than 500 ms (R^2 = 0.336, β = 0.580, p = 0.003). It is this duration of fixations that indicates the presence of sustained visual attention. Joint attention as a continuous alignment of fixing the attention of an adult and a child on an object, which lasted longer than 500 ms, may be shorter than 300 ms, same with the authors (Yu & Smith, 2017a). The main evaluation criterion is the time required to determine the location of the target. On the one hand, the mistakes made by children with hearing impairment are associated with the ability to maintain sustained visual attention, and on the other hand, with the speed of information processing.

Moreover, as a dependent variable in the regression analysis, the parameters of the number and duration of fixations on the sample were taken as a measure of maintaining visual attention by a child with hearing impairment in the learning process.

The number of fixations on a sample in a child with hearing impairment depends on the duration of the first non-target fixation (R^2 = 1, β = 0.486, p = 0.0001), the number of fixations (R^2 = 1, β = 0.629, p = 0.0001), the duration of non-target fixations (R^2 = 1, β = 0.069, p = 0.0001), the duration of the first fixation (R^2 = 1, β = –0.815, p = 0.0001) and the number of fixations longer than 300–500 ms (R^2 = 1, β = –0.085, p = 0.0001), synchronous with an adult less than 300 ms (R^2 = 1, β = –0.493, p = 0.0001). If non-target fixations are long, the hearing impaired child needs a large number of fixations on the sample. Attention to the sample is reduced if there was a long first fixation, and a child fixed on it for a long time, including the ones longer than 300 ms, and if these fixations occurred synchronously with an adult.

The duration of fixations on the sample in a child with hearing impairment depends on the duration of the first non-target fixation (R^2 = 0.998, β = 1.233, p = 0.0001), the duration of non-target fixations (R^2 = 0.998, β = 1.176, p = 0.0001), the number of fixations with duration less than 300 ms (R^2 = 0.998, β = 0.243, p = 0.0001), the duration of the first fixation (R^2 = 0.998, β = –0.769, p = 0.0001), the number of fixations lasting longer than 300–500 ms (R^2 = 1, β = –0.690, p = 0.0001), number of fixations (R^2 = 0.998, β = –0.199, p = 0.0001), duration of fixations (R^2 = 0.998, β = –0.004, p = 0.0001). That is, the duration of fixations on the sample depends on how long a child lingers in a non-target area, and directly on the duration of fixations and the ability to maintain visual fixations longer than 300–500 ms. It also depends on the number of fixations – as a parameter of the cognitive complexity of processing.

Discussion

In our study, the specificity of oculomotor activity in children with hearing impairment during synchronous with an adult and independent performance of a learning task was highlighted.

The change in oculomotor activity during independent and synchronous performance of the task confirms the assumption about the change in perceptual actions in episodes of joint attention. Joint attention during the synchronous performance of a task by an adult and a child helps to sustainably maintain the joint attention of children with hearing impairment. An adult gradually controls the perceptual activity of the child and contributes to the emergence of sustained visual attention.

In case of independent performance of the task, a longer time for the selection of target stimuli and a decrease in the duration of fixations on target stimuli will be specific. It is confirmed that, when performing the task synchronously with an adult, in oculomotor activity there is a greater relevance of fixations and an increase in the duration of joint attention and sustained maintenance of visual attention to training samples. A child with a hearing impairment, when performed synchronously with an adult, makes fixations on the training sample, on the working area (where a child drew a pattern). The child maintains constant attention for a longer and more often, including joint attention with an adult.

In episodes of joint attention in a learning situation, the synchronicity of interaction between a child with a hearing impairment and an adult is achieved through fixations that indicate constant attention – these are fixations lasting from 300–500 and above 500 ms.

However, with normative and atypical development, the functioning of joint attention in the learning process is different. It was confirmed in the comparative analysis of typically developing children and children with hearing impairment. Hearing-impaired children have fewer fixations lasting 300–500 ms, indicating constant visual attention. Moreover, it was found that there are also fewer fixations with 300–500 ms long, synchronous with an adult, indicating joint attention.

In children with hearing impairment, the speed of information processing changes: fixations are shorter in duration in both relevant and non-relevant areas.

One can draw a conclusion that the main specificity of oculomotor activity in children with hearing impairment is the change in the time of fixations. The gaze fixation time marker will be crucial for understanding the mechanisms of establishing joint attention in a learning process. That is, in a learning process in children with hearing impairment, the average time of fixations is shorter, the first fixation is shorter, including the first target fixation and target fixations in general. The time period when a child's eyes are focused on the target object decreases. Including children with hearing impairment, the time and number of fixations on the sample with the task decreases.

A decrease in the average duration and number of fixations can be considered as a measure of a decrease in the speed of information processing and an unstable involvement of the attention of a child with hearing impairment. A decrease in the time of fixation on target and non-target stimuli also indicates the cognitive complexity of the selection and priorities of information processing in the course of learning, a decrease in the involvement of the attention of a child with hearing impairment. Hearing impaired children make fewer fixations, while typically developing children process information in more detail (in terms of time and number of fixations) in both relevant and irrelevant areas.

These features of oculomotor activity in the process of learning in children with hearing impairment can be interpreted as the consequences of deprivation of sensory experience in the early stages of ontogenesis, associated with a violation of the auditory analyzer. It reveals the specifics of the functioning of the mechanism of joint attention and the possibility of compensation.

To understand the development of strategies for improving the perception of material in various areas of study, it is necessary consider that, compared with typically developing children, children with hearing impairment make fewer fixations on the training sample. Moreover, their duration on a training sample is shorter, and the duration of fixations on working training area is shorter. This requires special means of maintaining the attention of a child through synchronous performance with an adult and joint attention hold.

Our data help to capture the necessary conditions for adult-child interaction strategies to organize developmental conditions, learning and accumulation of social experience for typically developing children and children with hearing impairment. Among them are synchrony and the use of different ways to increase the duration of target fixations, maintain constant visual attention and joint attention with a child.

Through the indicators of impaired dyadic interaction between a child and an adult, the main difficulties that disturb a learning process were identified: measuring fixation time, search time, and changes in the frequency of saccades (fixation speed) in episodes of joint attention as a predictive marker of impaired joint attention and learning difficulties (for example, temporary delay or advanced reactions in a learning situation).

The task of forming joint attention in preschool children with hearing impairments is solved with the help of properly organized educational activities. This is possible through the use of various means of influence, explanation of material and an increase in the time of synchronous maintenance of a child's visual attention, the use of the direction of gaze as a hint, the initiation of joint attention (gestural guidance and showcase).

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Conflict of Interest Information

The author has no conflicts of interest to declare.