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THE SPECIFICITY OF FORMING STRATEGIES OF THE DYAD ADULT-CHILD WITH HEARING IMPAIRMENT IN THE PROCESS OF LEARNING: EYE TRACKING OF DOUBLE EYE TRACKING TECHNOLOGIES (DUET)

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Специфика формирования стратегий взора диады взрослый—ребенок с нарушением слуха в процессе обучения: айтрекинг технологии двойного отслеживания движения глаз (DUET)

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Abstract

The article is devoted to the application of dual eye tracking (DUET) eye tracking technology in the analysis of multimodal cooperation in the process of learning the child-adult dyad. The methodology is described and the double eye tracking (DUET) procedure was tested during the performance of a learning task in the adult-child dyad. Synchronous registration of the dyad's eye movements was carried out by two portable trackers in the form of Pupil Headset goggles. A comparative study of the synchrony of perceptual processes was carried out in a sample of preschoolers 4-6 years old: typically developing children and

Резюме

Статья посвящена применению айтрекинг-технологии двойного отслеживания движения глаз (DUET) в анализе мультимодального сотрудничества в процессе обучения диады ребенок–взрослый. Описывается методология и апробирована процедура двойного отслеживания движения глаз (DUET) в ходе выполнения обучающего задания у диады взрослый—ребенок. Синхронная регистрация движения глаз диады происходила двумя портативными трекерами в форме очков Pupil Headset. Проведено сравнительное исследование синхронности перцептивных процессов на выборке дошкольников 4–6 лет: типично развивающихся детей и детей с

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children with hearing impairment after cochlear implantation (with sensorineural hearing loss, ICD-10 class H90). An analysis of the ways in which the gaze of the adult-child dyad moves makes it possible to model the learning process as the emergence and dynamic transformation of an intersubjective connection between the perception-action systems of a child and an adult. Comparison of gaze patterns showed that contrasting groups of children use different perceptual strategies in the learning process: the specificity of eye movements of contrasting groups is manifested in the perceptual actions themselves and in the pattern of eye movements relative to fixations in relevant areas corresponding to the task. It was found that the oculomotor activity of an adult changes in the process of interaction with children of contrasting groups and is organized taking into account the specific features of the child's perceptual activity.

Keywords: joint attention, social attention, shared attention, learning, age development, preschool age, atypical development, hearing impairment, cochlear implantation, oculography, eye tracker.

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нарушением слуха после кохлеарной имплантации (с сенсоневральной тугоухостью, класс H90 по МКБ-10). Анализ путей движения взгляда диады взрослый—ребенок позволил смоделировать процесс обучения как появление и динамическое преобразование интерсубъективной связи между системами восприятия-действия ребенка и взрослого. Сравнение паттернов взгляда показало, что контрастные группы детей применяют различные перцептивные стратегии в процессе обучения: специфика движения глаз контрастных групп проявляется в самих перцептивных действиях и в паттерне движений глаз относительно фиксаций в релевантных областях, соответствующих задаче. Обнаружено, что окуломоторная активность взрослого видоизменяется в процессе взаимодействия с детьми контрастных групп и организуется с учетом специфики особенностей перцептивной деятельности ребенка.

Ключевые слова: совместное внимание, социальное внимание, объединенное внимание, обучение, возрастное развитие, дошкольный возраст, атипичное развитие, нарушение слуха, кохлеарная имплантация, окулография, айтрекер.

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Introduction

The development of joint attention in childhood involves increasing the child's ability to participate in parallel processing of information about their own attention and the attention of others, directing the focus of attention in such a way that it is focused on relevant perceptual information. In particular, the joint attention of a child and an adult impacts the effectiveness of maintaining visual attention in the learning process (Chen et al., 2021).

Visual attention is a process that selects details and information features that will fall into an individual's field of view , which should be focused on, and which will be ignored and filtered out; it allows the selective processing of visual information by prioritizing it in the field of view so that the focus of attention of two or more people was not only directed to the same aspect of the object, but also so that the communication partners would be mutually aware of their joint participation in this process and understand the intentions of the other person.

An analysis of the gaze movements of the adult-child dyad in eye-tracking studies allows us to model the learning process as the emergence and dynamic transformation of an intersubjective connection between the perception-action systems of a child and an adult (Shvarts, 2018). While the child is experiencing sensorimotor coordination, the adult's perception is triggered from the child's current action until the adult determines the optimal moment for the necessary intervention.

In this methodology, the learning process is explained as the emergence of a new form of sensorimotor coordination, which is later conceptualized by cultural semiotic means (Radford & Sabena, 2015). In the process of joint action, sensorimotor coordination appears (Duijzer et al., 2017) — the anchors of attention. The attentional anchor is an imaginary perceptual strategy that occurs in humans as a means of facilitating the coordination of sensorimotor circuits (Abrahamson & Sánchez-García, 2016; Hutto & Sánchez-García, 2015).

Yet, for a long time there were no research tools for displaying how a child and an adult perceive the world when they act in it synchronously. With the development of eye-tracking technologies, it became possible to more objectively trace the transformation of a child's perceptual processes under the influence of learning (Monroy et al., 2021).

In order to study the learning process, the eye movement registration method was used in a number of studies related to the perception of visual materials by children during learning to explore its characteristics that contribute to improving understanding of the material and the restructuring of a child's perception under the influence of learning (Abrahamson & Sánchez-García, 2016; Duijzer et al., 2017).

The general conclusions of eye-tracking studies on the changes of oculomotor activity during the learning process can be universal: as a result of learning, perceptual actions are characterized by greater curtailment, as well as the ability to quickly and more reliably identify areas relevant to the task, using generalized knowledge as an indicative basis for perceptual actions; the speed of information perception changes (Abrahamson & Sánchez-García, 2016; Belenky et al., 2014; Bielikova et al., 2018).

It was shown in studies on the evaluation of learning outcomes through the parameters of oculomotor activity that the oculomotor activity of an expert/teacher and a beginner/student differs in that:

• he speed of perceiving information changes: fixations were longer for students, but fixations in relevant areas were longer for experts. In the learning process, fewer and fewer students pay attention to irrelevant information.

• strategies for solving problems with a choice of answers change: experts spend much time studying the conditions and then moving almost immediately to the correct answer, while beginners study the proposed options at length.

• the pattern of eye movements of experts is more consistent with the task.

That is, from the point of view of the analysis of the stages of learning, there is a change in the pattern of eye movements as a result of the learning impact.

A technological breakthrough in the simultaneous tracking of the visual behavior of two people with an eye tracker (double eye tracking, DUET) allows you to explore how a child perceives the world and how an adult (teacher) influences it when in response to perceiving their actions, they perform response actions or control them; how joint attention with an adult contributes to the emergence of new sensorimotor schemes and to the development of subjective perceptual activity in a child.

Dual Eye Tracking Technology (DUET) is a new tool that first appeared approximately in 2005 in cognitive linguistics in the study of collaborative decision making (Brennan et al., 2008; Pietinen et al., 2008).

Using the DUET technology researchers can simultaneously record eye movements of two participants., with new horizons opening up in the analysis of joint attention and changes in perceptual processes under the influence of learning in the adult-child dyad. DUET has the potential of analyzing the synchrony of two people in the field of learning by simultaneously drawing the participants' attention to one object. It provides for a multimodal analysis of joint work in a common space (Shvarts et al., 2018).

DUET technology enables the synchronous tracking of the eye movements of two people seated in front of a monitor (Pietinen et al., 2008; Lilienthal & Schindler, 2017; Schneider et al., 2018; Shvarts, 2018) or two synchronized monitors (e.g., Jermann et al., 2010; Richardson et al., 2007; Sharma et al., 2015; Bielikova et al., 2018) or operating in a naturally flexible environment (e.g., Pfeiffer & Renner, 2014; Schneider et al., 2018).

The first detailed comparison of behavioral eye movement patterns and attention patterns of children and their parents was made in two free play contexts: one with new objects with unknown names to be learned (learning condition), the other with familiar objects with known names (Yu & Smith, 2017). It has been shown that the adult's focus of attention and the response and initiation of joint attention influenced the child's joint attention.

Several studies of shared attention during collaboration have used DUET technology (e.g., Belenky et al., 2014; Schneider et al., 2018), including online learning with MOOCs (Sharma et al., 2015), a study of joint attention initiation versus joint attention response in infants and adults in an experimental laboratory setting, or a DUET analysis of in vivo infant-adult dyad communication (Yu & Smith, 2016). Also, the results were obtained in a study of a joint game of Tetris (Jermann et al., 2010), where pairs of experts and beginners were examined. It was shown that the perceptual actions of both experts and novices became more similar to each other compared to the corresponding eye movements of the participants in the expert-expert or novice-novice pairs.

Studies by K. Dindar, T. Korkiakangas, A. Laitila, and E. Karna (2017) show that adults have different attitudes to a change in a child's gaze, depending on how they manifest themselves in the flow of other actions. Experts can reveal to beginners how they themselves attend to the target area (Goodwin, 1994), highlighting its functions that are important for the task or required actions (for example, Jamet, 2014; Ozcelik et al., 2010), through various forms of visual cues (Boucheix et al., 2013). That is, the mutual transformation of the perceptual processes of both the adult and the child at the moment of joint attention is emphasized.

Thus, using synchronous eye tracking, researchers are identifying a new unit of analysis – an “intersubjective joint perceptual system” of an adult and a child involved in learning activities, and not just the individual trajectories of gaze movements of an adult and a child separately (Radford & Sabena, 2015). This makes it possible to trace the synchronism of visual attention and the ways of achieving joint attention in the adult-child dyad, to “reveal” what is happening inside the process of establishing joint attention, to trace the ways of achieving synchrony of perceptual processes and to analyze the critical moments of their mismatch.

Therefore, we can analyze intersubjective perceptual coordination and discoordination between: 1) the focus of a child’s attention and the focus of an adult’s attention; 2) the actions of a child and the focus of attention of an adult; 3) the actions of an adult and the focus of attention of a child. Two people can thus be considered as two intersubjectively connected perception-action systems or as a single distributed intersubjective system, thereby revealing the interaction as a dynamic self-organizing system. “Intersubjective sensorimotor coordination emerges by anticipating and attentively tracking each other’s actions” (Abrahamson & Sanchez-Garcia, 2016); such cooperation in the learning process is seen as a classic triadic structure of the relationship between the object of learning, an adult and a child, which inevitably includes the mechanism of joint attention.

A. Shvarts’s research shows that the scanning paths of two people’s eye movements on the screen can be combined through new technological possibilities, since the synchronized data provide coordinates for each tracker. Shvarts expands the understanding of pedagogical interaction as an intersubjective dynamic connection between the systems of perception and action. It comes from the need for objective evidence that can be tracked in multimodal data, including dual gaze tracking of a child and an adult. Shvarts made a detailed analysis of the advantages and limitations of existing technical solutions for double eye tracking (DUET) in connection with pedagogical research focused on joint attention in multimodal learning using the example of teaching mathematics (Shvarts, 2018; Shvarts & Abrahamson, 2018; Shvarts et al., 2018; Shvarts & Zagorianakos, 2016). In this example, the DUET (DUal Eye-Tracking) for the Pupil technology has been worked out in detail and a unique program has been created for processing the recording data of Pupil-labs paired eye-trackers.

The experience of previous studies shows that when using DUET analysis, in order for an episode to be encoded as a manifestation of joint visual attention, it is considered in the spatial (fixation in areas of interest) and temporal coordination of eye movements in the context of multimodal interaction (for example, gestures and verbal utterances) (Shvarts, 2018; Kassner et al., 2014; Monroy et al., 2021; Schroer & Yu, 2021).

Studies using double eye-tracking can be qualitatively expanded with the help of double tracking of the gaze movement of a child and an adult, followed by the reconstruction of synchronous gaze shift (Dindar et al., 2017), which makes it possible to determine the similarity in the spatiotemporal path of movement observed between the gaze of an adult and that of a child (Hoch et al., 2021; Schroer & Yu, 2021).

We found it essential to compare contrasting samples of children in order to understand the synchronism of perceptual processes and to define the role an adult plays in the organization of a child's visual attention. It also contributed to our understanding of how the adult's perceptual activity is organized depending on the specifics of the child's perceptual activity. The comparative analysis was aimed at typically developing children and at a sample of children with hearing impairment.

Little is known about how the limited sensory experience of hearing loss affects the coordination of attention between a child and another person, and what means can be used to establish episodes of joint attention in a child with hearing impairment. And yet, an urgent task of modern psychology is to define effective ways of learning, taking into account the specifics of the mental development in people with impaired auditory function, and to establish the possibilities and ways to compensate for anomalies of varying complexity. This requires a psychological substantiation of the most effective ways and methods of pedagogical influence on children with hearing impairment.

It is known that children with hearing impairment can use their own sensorimotor skills, adult speech and other social cues to coordinate joint attention for learning purposes (Yu & Smith, 2017). This is the way children with cochlear implants develop a unique verbal-gestural bilingualism, which allows several streams of information to be transmitted in parallel. Hearing impaired children rely on the foundation of multisensory functioning (coordination of visual, language and motor cues) to share social experiences/interests (Ibid.). The distinctive sample provides for systematizing universal and specific multimodal means of establishing joint attention in a learning situation in typically developing children and in children with hearing impairment with cochlear implants.

Despite the results obtained in previous studies, there has still been little research on the effective restructuring of perception by focusing attention on task-relevant elements in children with hearing impairment. Only a few studies on samples of children with hearing impairment note that the time spent on joint attention is often reduced in deaf children, and they are often less likely to respond and expand their initiative and communicative actions (Mundy, 2017). Hearing-impaired children use the information they gain from observing their parents' movements to focus on them with their parents (Yu & Smith, 2017). The attraction of joint visual attention is not accidental, as it relies on the basis of multisensory functioning (coordination of visual, language and motor signals) in order to share social experiences and interests. In turn, parental actions with objects support and expand the child's visual attention to those same objects (Ibid.).

One of the overarching questions in the field of cognitive development of children is how the selective attention of children with hearing impairment is organized to facilitate learning. The eye-tracking method provides an approach to describe and explore the multiple pathways to coordinating joint visual attention in hearing impaired children in a learning situation.

The dual eye tracking methodology identifies potential multiple ways in which children (with or without hearing impairment) focus their attention on adult and learning material during the process of learning and how the adult helps support the child's joint attention.

The purpose of the study is to analyze in detail the indicators of the synchronous gaze of an adult and a child during learning using the technology of double eye tracking (DUET), to model the joint perceptual action of a child and an adult, and to reflect on the moments critical for establishing joint attention necessary for effective learning of typically developing children and children with hearing loss.

Procedure and Methods

Empirical Sampling of the Study

The study sample consisted of preschoolers aged 4 to 6 years, of which 7 were preschoolers with hearing impairment (sensoneural hearing loss, class H90 according to ICD-11; the average hearing threshold at frequencies of 0.5, 1, 2 and 4 kHz is more than 90 dB), 6 girls, 1 boy, mean age 5.2. Cochlear implantation was performed at the age of three years. The sample was adjusted according to the time of occurrence of the hearing defect, the conditions of learning and the time of cochlear implantation.

Before and after cochlear implantation in the setting of a specialized kindergarten, children received an adjustment assistance in developing their language skills, including the sensory basis of verbal speech perception (visual, auditory-visual, tactile-vibratory); imitation of the subject and speech actions of an adult; the ability to apply in communication any learned speech actions and means; the ability to correlate the spoken and written word with the designated content; and the ability to grasp analogies in a linguistic form.

Preschoolers with a cochlear apparatus in this group are able to perceive sound signals, perceive non-speech sounds and respond to them. Preschoolers with a cochlear apparatus, as a special group of children, are in the period after the restructuring of communication interaction with adults and therefore they retain a special (transitional) status.

Preschoolers have levels of cognitive development sufficient for the study, thresholds for speech perception and recognition, and understanding of addressed speech. Children are trained to use sound-amplifying equipment for collective and individual use.

Parents of children are without hearing loss. Parents are involved in the children's education when they stay at home.

Parents are trained in the necessary means of speech perception and communication with preschoolers with cochlear implants.

The contrast group consisted of typically developing preschool children aged 4–6 (6 girls, 1 boy, mean age 5 years).

Thus, 14 dyads participated in the study:

• 7 dyads of the adult experimenter and a child with hearing impairment.

• 7 dyads of the adult experimenter and a typically developing child.

The same adult experimenter participated in the research process with different children. This enabled the description of the specifics of achieved ways of synchronization of perceptual systems precisely on the basis of a child's individual characteristics and how the perceptions of different groups of children change specifically under educational influence in standardized conditions.

Experimental Procedure

For the study, an experimental situation was created to trace the learning difficulties in children with hearing impairment associated with joint attention skills.

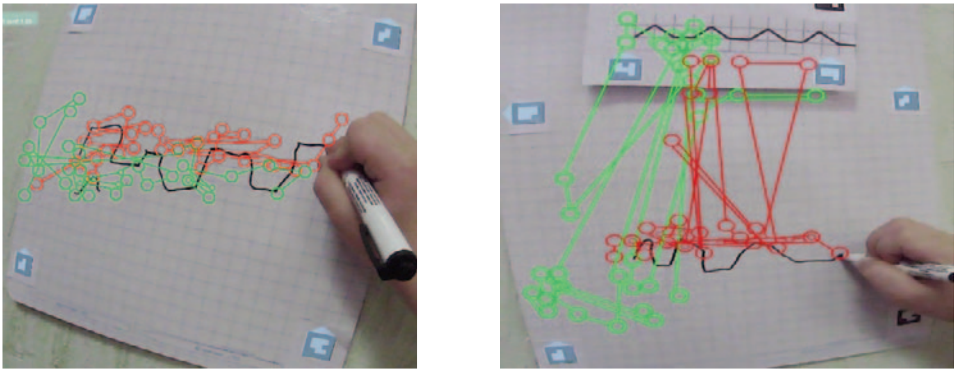
In order to define the specifics of multimodal means (verbal and non-verbal) of establishing joint attention, two series of experiments were carried out.

In the first series of the experiment, a visual sample with a pattern was placed in front of the child, and they had to draw exactly a pattern identical to the visual sample. During the instruction, the experimenter explained to the child the task of copying exactly the same pattern. That is, the series assumed the independent implementation of a program of actions by the child according to a visual program. In the experimental procedure, one sample was presented (as in Figure 1). The sample was selected from a training program used by the preschool where children were trained.

In the second series of the experiment, the 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; that is, the series assumed the joint synchronous execution of an action program and the adult's step-by-step control, planning and control are distributed between the adult and the child. The child was given the following instruction: "Now we will draw a pattern. You should listen carefully to me, I will say how many cells and in which direction you should draw a line. Only the line that I will say is to be drawn. The next line must be started where the previous one ends, without taking the pencil

Figure 1

An Example of Our Processing a Frame from Data



off 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. During the experiment, the child was offered one graphic dictation (as in Figure 1). The pattern for the dictation was chosen from the training program implemented by the preschool institution where the children studied.

It is in the second series of the experiment, in our opinion, that intersubjective sensorimotor coordination of an adult and a child appears by anticipating and carefully tracking each other's perceptions and actions, and it becomes possible to trace episodes of joint attention. The adult gradually literally controls the child's perceptual activity and contributes to the emergence of new sensorimotor circuits. It is here that the synchronism or mismatch of perceptual systems is important to maintain joint attention in the learning process. While the child is experiencing sensorimotor coordination, they draw a pattern at the direction of an adult, and the adult's perception is triggered by the child's current action until the adult determines the optimal moment for a necessary intervention.

For the experiment, a board lined with a checker was placed in front of the child (cell size 1 by 1 cm; board size: width 24 cm, length 34 cm). The form with the sample was attached to the board in the first series of the experiment.

The height of the lower edge of the training board is 58 centimeters above the floor (according to GOST Standard 11015-93).

The distance from the child's eyes to the blackboard is at least 30 centimeters (requirements for the conditions and organization of education in educational institutions).

The distance from an adult to the board is at least 30 centimeters.

The distance between a child and an adult is about 30 centimeters.

Seat height of chairs 34 cm, width 29 cm

Equipment and Methods

Eye movement registration was carried out using two portable trackers in the form of Pupil Headset goggles (Pupil Labs).

The portable tracker detects the pupil, determines the direction of the gaze, and calibrates and finds markers that highlight areas of interest. Pupil tracking technology used was the Dark pupil with 3D model. Pupil fixation parameters were 3D eye models. Sampling rate 200 Hz @192×192 px. A high speed scene camera with 480p/120hz @ vga fixation was used. Eye movements were recorded in the binocular mode with a frequency of 200 Hz. Shooting the real world is carried out in 480p resolution. An algorithm based on the determination of the angular velocity with an additional criterion of the fixation speed is used to describe the fixations. The accuracy of determining the coordinates is 0.60 degrees; gaze detection accuracy was 0.08 degrees. Camera delay was 4.5 ms and the processing latency depending on the CPU was > 3 ms.

The data obtained using 3D pupil detection were processed and visualized in the Pupil Player.

The data were initially calibrated prior to the experimental gaming session in a 1-point pupil detector scoring system (as far as we can be sure of this measurement (data have greater than ~0.6 confidence)). Calibration was 5-point, on the monitor. To ensure tracking quality, we manually calibrated the data, for example if children touched the glasses or made quick head movements that caused the glasses to move.

Pupil Capture software processes audio and video streams, detects the pupil, determines the direction of gaze, calibrates and finds markers, transmits data over the network and saves the results. The Pupil Core software collects these test points and the pupil position data during calibration. It then correlates them over time and computes a mapping function that is used to evaluate gaze for future pupil movement data. Calibration accuracy can be visualized using the Accuracy Visualizer. The plugin displays the difference between the control points and the corresponding gaze positions that were recorded during calibration.

We have used two Pupil-Labs eye-trackers. For synchronous tracking of eye movements in the experimental procedure, the eye trackers were worn by both a child and an adult.

Mobile eye trackers provide freedom of movement in relevant conditions and allow free manipulation. The recording data of the eye tracking recordings of two participants are synchronized after approximately 1 ms. This technical solution makes the qualitative frame-by-frame analysis possible and efficient.

For dual tracking recording, each device is connected to a separate laptop (we used a Lenovo Legion).

The Pupil-Labs recording system (Pupil Capture) is already equipped with a synchronization plugin (Time Sync) to record data with consistent timestamps.

Another plugin (Pupil Groups) allows the user to start recording to multiple devices from a single computer; thus, data from two eye-trackers are synchronized.

Black and white markers can be placed on any surface in the environment (for example, on a blackboard or a worksheet) through the Pupil-Labs system. Later during the analysis (which is done by Pupil Player), this surface can be recognized automatically (by the Offline Surface Tracker plugin).

The position of the eye in a surface-based coordinate system can be calculated by a homology transformation from the original coordinates in the visual scene and then stored with appropriate timestamps.

Synchronization of two eye-trackers can be achieved at the analysis stage, for example, by a special wave of the hand, which is captured by both scene cameras during recording (Lilienthal & Schindler, 2017; Shvarts, 2018; Shvarts & Abrahamson, 2018).

With the help of DUET technology, research can be conducted in relevant conditions, where participants share space and can gesticulate and make eye contact.

All information about multimodal interaction is collected in one video package, which can be qualitatively analyzed.

The technology has a number of limitations that were taken into account, determined by the ergonomics of the system (both participants should sit very close to each other) and by analysis (this method does not allow video processing, but only a series of stable images). Precise timing is also a problem, as this is done after recording and is done manually. An unstable video frame rate from an external camera can be an obstacle to accurate time synchronization through the video. In many cases, the fixation points are close to each other, so they are compressed into a knot and it is not technically possible to accurately display each fixation.

Procedure and Technology

The technology for displaying synchronous trajectories of the eye movements of a child and an adult was implemented in several stages:

1. Children's gaze data videos and adult's gaze data videos were calibrated (30 fps).

2. To synchronize two videos received from the eye-trackers of a child and an adult, a visual stimulus was used (a sign given by the movement of an adult experimenter's hand to start a simultaneous countdown of the experiment). A countdown of fixations for 2 videos began after that time. On each of the videos, a visualization of the spatial movement of the gaze direction (graphs of gaze movement) was made, while the points of fixation of the gaze were displayed as circles. To build heat maps, the distribution of viewpoints on the surface marked with special markers is visualized. The gaze movement graph helps to identify and display the areas of interest that the respondent most often and least looked at, where their attention was focused and what elements they ignored and noticed in visual attention by the visibility of elements of reality for the child, the points of focus of their attention, and the mental load and distractions.

3. First, we aligned the video with eye trajectories from an adult and a child in a dyad, obtaining a series of frame-by-frame events in which both were (or were not) focused on the same area of interest, indicated by special markers (a board, a sample with a task).

We assumed that joint attention would be recorded as a permanent "alignment" of adult and child fixation on the same area of interest that lasted longer than 500 ms, including brief glances elsewhere, if each of these brief glances was shorter than 300 ms (Yu & Smith, 2017). Joint attention was methodologically defined as lasting at least 500 ms and might include short glances (<300 ms) away from the observed object (Ibid.).

In this regard, we took fixations that fell into the heat map in a relevant area, indicated by markers, and the duration of fixations had a period of 50 to 600 ms. In such cases, special markers are used as reference points to establish a common visual field, on which the gaze movement scan is superimposed (Lilienthal & Schindler, 2017; Schneider et al., 2018.

4. After selecting all the fixations of an adult and a child in a graphical editor, a scheme of gaze movement is built using them during the selected test period. The gaze movement diagram shows the gaze direction during the selected time period, with each point on the line representing the position of the gaze at a frequency of 60 Hz (in many cases the points are close to each other, so they are compressed into a knot, which corresponds to fixation). After collecting information about the gazes of an adult and a child in the same coordinate system, we draw their gaze

positions on the frame to depict the gazes' paths. The gaze trajectories are drawn on the image of the initial state of the surface and data on eye movements are synchronized with the scene of videos from cameras.

Two lines on the frame represent processed gaze paths: adult (red line) and child (green line). Circles of red and green indicate the position of the gaze (fixation) of an adult and a child, respectively.

Thus, step by step, we visualize the synchronized gaze data of the adult-child dyad in a common coordinate system. The data are available as a video with a surface overlaid with the gaze trajectories. By following the line, we can reconstruct how the gaze trajectory moved.

Results

Our analysis focused on modeling the coordination between child and adult visual attention through dual eye-tracking technology during learning.

In our study, modeling is limited to visual and motor modalities: a child draws a pattern, and an adult observes the action process. The connection of perceptual actions with practical actions is visualized, which manifests itself in their extended external-motor character.

These episodes provide convincing information for analyzing the situation, the process of forming an intersubjective relationship between an adult and a child in the learning process.

Through the use of synchronous eye-tracking, we superimpose the eye movements of an adult and a child involved in a learning activity. Using the superimposed trajectories of eye movement, we were able to trace the moments of the appearance of synchrony of visual attention in the adult-child dyad and analyze the critical moments of their mismatch. By superimposing the eye movement trajectories of an adult and a child, we were able to analyze the similarities/differences in the spatiotemporal path of movement that are observed between the eyes of an adult and a child (Hoch et al., 2021; Schroer & Yu, 2021).

The method of qualitative assessment of synchrony included the analysis of perceptual coordination and discoordination between: 1) the focus of the child's attention and the focus of the adult's attention; 2) the actions of the child and the adult's focus of attention; 3) the actions of an adult and the focus of attention of a child.

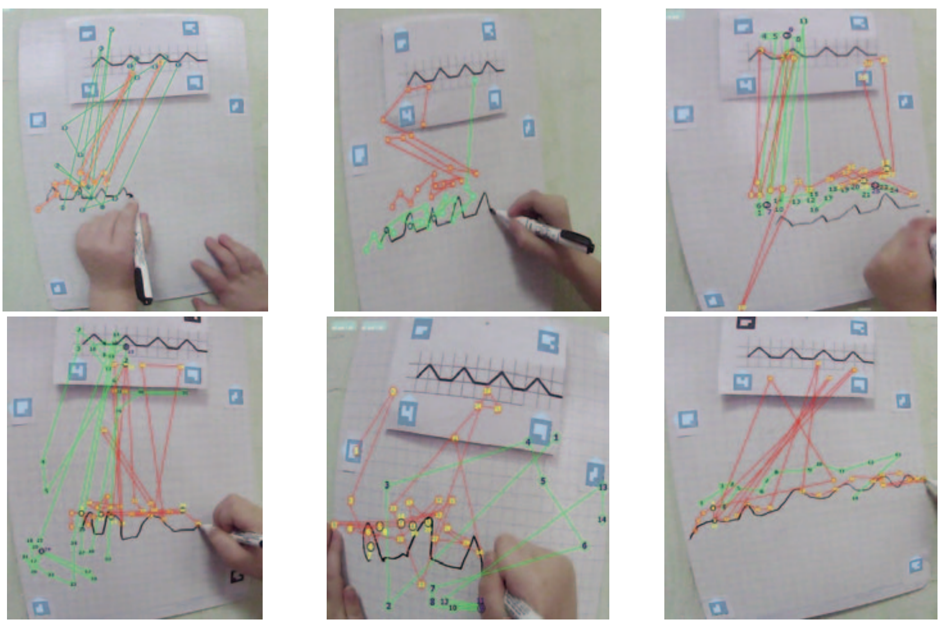
To do this, we (1) studied the constancy of gaze patterns and variations in gaze patterns of an adult in the learning process during the synchronous and independent performance of a learning task by a child with hearing impairment and by typically developing children, and (2) investigated the constancy of gaze patterns and variations in gaze patterns of a child with hearing impairment and of typically developing children in the process of learning including a task fulfilled simultaneously with an adult and independently .

We relied on the similarity/difference in a sequence of fixations between the adult and the child, the synchronistic appearance of these fixations, the spatial and temporal coherence or mismatch between the fixations of the adult and the child, and on either similar or different eye movement trajectories in the dyad. That is, it was important to trace where the fixations of an adult were located in the selected period of time and where the child's fixations were at that moment. The criterion was the spatial coordination/discoordination of the trajectories of gaze movements of an adult and a child, and the consistency of the adult and child focusing within an episode of joint attention. Qualitative analysis included an analysis of changes in the trajectory of eye movement and fixations of an adult when working with typically developing children and with children with hearing impairment during the independent and joint performance of a learning task. We also analyzed changes in the trajectory of eye movement and fixations of typically developing children and children with hearing impairment during the independent and joint performance of a learning task.

In the first series of the experiment, after the adult gave instructions, the child drew a pattern according to the sample. According to the trajectory of eye movements, it can be noted that when the child acts independently according to the proposed model, the intersubjective connection of the dyad is clearly manifested in controlling perceptual actions. Using the example of eye trajectory overlays in the process of teaching children with hearing impairment, we see that an adult performs a complex eye movement pattern that first scans the child's actions and then checks with the sample, revealing errors and the very course of the child's actions (Figure 2). Figure 2 shows examples of gaze movements of six hearing impaired children and an adult in the first series of the experiment.

Figure 2

Graphs of Gaze Movements of Children with Hearing Impairment and an Adult in the First Series of the Experiment



Note. Hereinafter: the red line and circles are the trajectory of an adult's gaze, the green line and circles are the trajectory of a child's gaze.

Graphs of gaze movements of children with hearing impairment and an adult in the first series of the experiment (the red line and circles are the trajectory of an adult's gaze, the green line and circles are the trajectory of a child's gaze)

At the same time, according to the trajectory of eye movements and fixations of the dyad, it is clear that the perceptual strategies of a child with hearing impairment and an adult develop independently of each other and asynchronously (the spatial localization and the sequence of fixations of an adult and a child are not coordinated). Different patterns of eye movements and fixations were observed in children with hearing impairment and in adults.

At the same time, children with hearing impairment make repetitive eye movements from the previously drawn element to the sample, comparing the actions with both the previously completed part and the sample. The child literally develops schemes for coordinating actions and perceptions to solve the target problem. Perceptual actions of the child are aimed at:

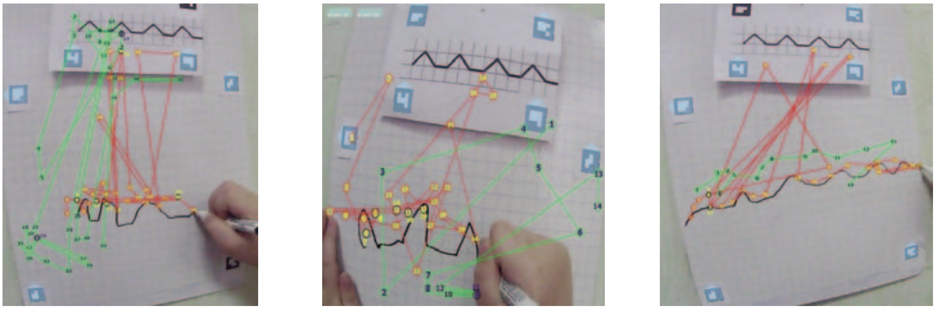
- detection and discrimination (perception of a sample with subsequent formation of its perceptual image);
- comparison or identification (perceived action is identified with an image, or a model);
- identification and identification (removal of the corresponding standard from memory and categorization of the object) and actions in relation to the standard (comparison with the standard);
- control actions.

The child has a continuous comparison of perception with the original, verification and correction of the image. The idea has been confirmed that children develop and use psychological constructions of new perceptual structures, which evolve as their heuristic means of managing effective actions for solving a problem.

To identify the specifics of the perceptual processes of children with hearing impairment, a comparative study was conducted on a sample of an adult dyad with typically developing children. It was found that the trajectories of eye movements have a different specificity (Figure 3). Figure 3 shows examples of eye movements for three different typically developing children and an adult.

Figure 3

Graphs of Gaze Movements of Typically Developing Children and an Adults in the First Series of the Experiment



When performing a task with typically developing children, an adult and a child show more synchrony of perceptual actions, and the trajectories of eye movements and the sequence of fixations of the dyad are more similar.

Typically developing children are less likely to refer to the pattern than children with hearing loss.

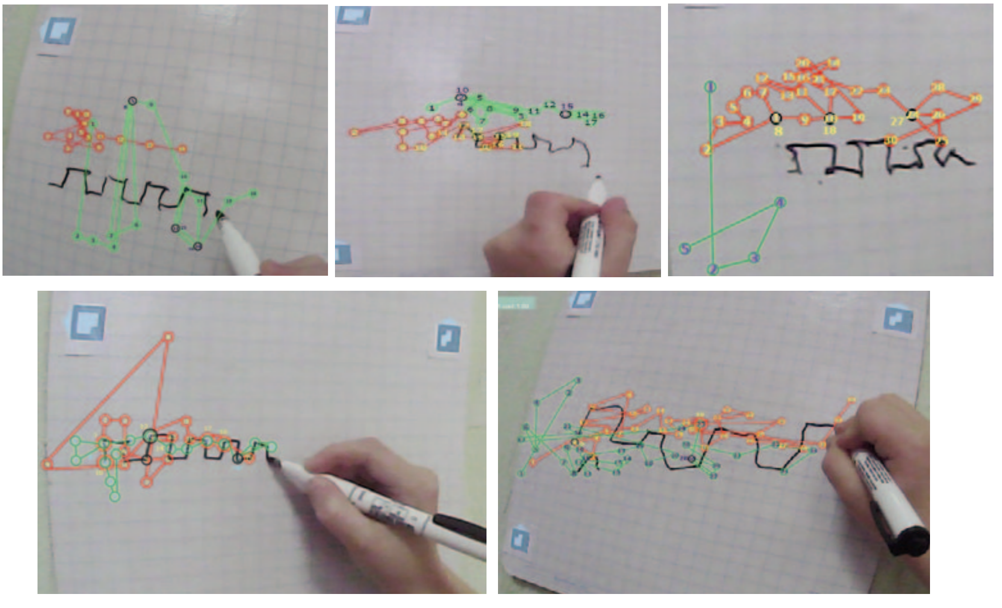
An adult in the process of teaching typically developing children makes fewer fixations, that is, there are more controlling perceptual actions when performing a task with children with hearing impairment.

In the second series of the experiment, the task was to trace how the organization of the perceptual processes of both the adult and the child occurs at the moment when the adult simultaneously controls the perceptual activity of the child and contributes to the emergence of new sensorimotor schemes. It should be noted that in the second series of the experiment, children were given verbal instructions for a graphic dictation: they had to draw a pattern without a visual sample, the task was performed only synchronously according to the verbal instructions of an adult. In this experimental situation, it was necessary to document the emergence of an intersubjective connection between the perception-action systems of the child and the adult.

On a sample of dyads of an adult and children with hearing impairment, there is a greater synchrony of the perceptual actions of an adult and a child than in the first series of the experiment (Figure 4).

Figure 4

Graphs of Gaze Movements of Children with Hearing Impairment and an Adult in the Second Series of the Experiment



Despite the discoordination in perception, adults find a coherence between the perception of the adult and the actions of the child, which also supports the adult-child model as dynamically connected in a single visual space. We assume that this asynchrony is reduced due to the fact that the effect of "compatibility" and speech regulation of actions is involved, which allows an adult to track the child's activity more synchronously and there is a greater synchrony of perceptual systems.

The sensory effects of the response actions of an adult occur in a timely manner after the action is performed due to the synchronism of visual attention to the same visual space and actions in it. The synchronism of perceptual processes and the division of a common task allow the adult to more accurately predict the child's actions and move from predicting the action to choosing the appropriate additional action and organizing the child's perceptual activity.

Thus, when visualizing the paths of eye movement, we see how a child's perceptual actions are organized under the influence of an adult and the specifics of their perceptual processes., while the adult's perceptual processes are mutually rearranged.

In the dyad of an adult with typically developing children, as well as in the first series of the experiment, differences from the dyad of an adult with children with hearing impairment were revealed (Figure 5).

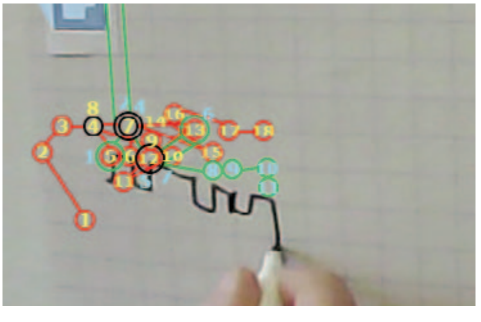
It is also worth noting that in the first and second trials, the adult made more fixations than the child (Table 1).

This is most likely due to the fact that the adult performs more perceptual actions, since in the process of learning they predict the child's actions and must move from predicting the child's action to choosing the appropriate control action at the appropriate time. Due to the perceptual actions of the adult, synchronization and maintenance of joint attention with the child occur. A general focus is needed for:

- predictions of the child's actions,
- preparing action in response to events that will occur,
- coordination of actions,
- understanding by adults of how the child adjusts their actions in time and space.

Figure 5

Graphs of Gaze Movements of Typically Developing Children and an Adults in the Second Series of the Experiment



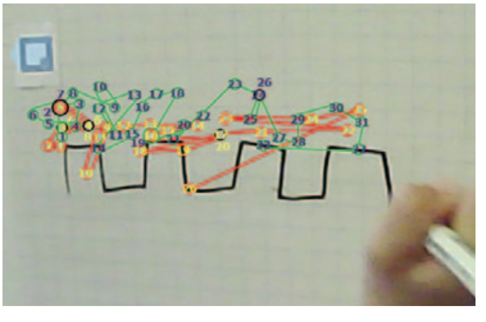


Table 1

The Average Number of Fixations of an Adult and a Child in the First Series of the Experiment

		M	**SD**	***p***
Sample 1	Fixation of the child	20.83	6.73	.05
	Adult fixations	25.33	8.35	
Sample 2	Fixation of the child	17.66	9.39	.03
	Adult fixations	23.83	7.13	

It is likely that it is due to the perceptual actions of an adult that visual attention is established and maintained in the learning process. However, it is precisely these difficulties in the perceptual actions of an adult in the process of interacting with a child with a hearing impairment that will not affect the failure of synchronization and maintenance of joint attention to occur.

Next, a quantitative analysis was made of the established episodes of joint attention. To understand the synchronism of perceptual processes, not only spatial characteristics (areas of interest) are important, but also characteristics of fixation time (Shvarts, 2018; Yu & Smith, 2017).

We used the criterion of the degree to which an adult and a child directed their gazes at the same object at the same time and how long this fixation lasted (Yu & Smith, 2017).

Two main categories of gaze fixation duration were analyzed: short gazes, less than 300 milliseconds (the threshold for sustained attention used in previous studies (Yu & Smith, 2016) and long gazes lasting normally from 300 to 500 milliseconds. In addition, it is planned to use gaze fixations of 300 milliseconds or more associated with joint attention or moments when the adult also looks at the selected area.

For quantitative confirmation of the data on the synchrony of dyads, we separately selected the fixations of a child and an adult and compared how the number of occurrences of simultaneous fixations lasting 300–500 milliseconds in an adult changes when working with typically developing children and with children with hearing impairment. In this way, we can confirm the differences in joint attention when working with typically developing children and children with hearing impairment.

Using the Student's t-test, fixations of 300–500 milliseconds in duration were compared in an adult, including those observed simultaneously with a child (Table 2).

In working with children with hearing impairment, an adult has fewer fixations indicating constant attention and joint attention than in working with typically developing children. A distinctive feature is the reduction of fixations lasting 300-500 milliseconds as a parameter of sustained attention and the same fixations lasting 300-500 milliseconds simultaneously with the child. This confirms the qualitative data on the greater synchrony of perceptual processes between an adult and typically developing children.

Discussion

Using double eye-tracking technology (DUET), we recorded the perceptual activity of an adult and a child in a common visual space during learning.

Table 2

The Average Number of Fixations of an Adult and a Child in the Second Series of the Experiment

Parameter	Group	Mean ±RMS mean	*t*	*p*
Number of fixations lasting 300-500 milliseconds	Adult with typically developing preschoolers	14.75±0.49	4.636	0.0001
	Adult with hearing impaired preschoolers	8.75±0.87		
Number of fixations longer than 500 milliseconds	Adult with typically developing preschoolers	9.2500±1.08150	2.938	0.008
	Adult with hearing impaired preschoolers	5.12±0.83		
Number of fixations lasting more than 300-500 milliseconds simultaneously with the child	Adult with typically developing preschoolers	12±.70	6.168	0.0001
	Adult with hearing impaired preschoolers	5.12±0.70		
Number of fixations lasting more than 500 milliseconds simultaneously with the child	Adult with typically developing preschoolers	8.25±0.97	2.918	0.008
	Adult with hearing impaired preschoolers	4.25±0.83		

Comparison of gaze patterns showed that each group of children with hearing impairment and typically developing children used different perceptual strategies in the learning process:

• The specificity of the eye movements of contrasting groups is manifested in the perceptual actions of detection, comparison, identification and control. Differences between typically developing children and children with hearing impairments were found precisely in the perceptual structures that control effective actions.

• Differences appear in the pattern of eye movements. Children with hearing impairment make many irrelevant fixations in non-target areas for the task, and the eye movement pattern is less appropriate for the task: fixations often appear not in the area of the training form, sample or training field as the target for the task, but on objects and things that are not related with the completion of the learning task.

• Perceptual actions in typically developing children are more convoluted, there are fewer fixations, fixations occur in relevant areas (a training sheet, a sample or a training field).

• In typically developing children and children with hearing impairments, the process of selecting information features proceeds differently: the sequence and number of fixations differ when analyzing a training sample.

Differences in the moments when synchrony and joint localization appear between the eye movements of an adult and typically developing children and children with hearing impairment, have been recorded, which will further a more detailed analysis of joint attention, its origin and maintenance.

It is important to discover both the specifics of the oculomotor activity of children with hearing impairment and typically developing children and changes in the oculomotor activity of an adult in the process of interaction with children from contrast groups.

Comparison of two series of experiments revealed the features of perceptual actions with different types of instructions and the degree of compatibility and independence of the task.

Therefore, a greater degree of synchrony of perceptual processes was observed in the second series of the experiment, with a more pronounced adult participation and synchronous performance of the task with the involvement of speech means of control, in the dyad of an adult and a child.

Both series of the experiment show that joint attention in the learning process is used in anticipatory controlling perceptual actions of an adult. The synchronism of perceptual processes is effective for proactive control of actions, including internal signals concerning one's own actions in relation to the actions of the child.

In the first series of the experiment, even when the child completes the task on their own in the process of learning, the adult monitors the actions performed by the child and anticipates subsequent actions and the focus of attention. Perceptual coordination is achieved through tracking perceptual actions for the child. These are sensorimotor behaviors that can be seen as preceding or at very early phases of joint action or joint comprehension (as in studies by Brooks & Meltzoff, 2005). That is, there is still no obvious interaction: the child acts while the adult observes, but they do not intervene in any interpretive way as they only occasionally prompt further motor actions, but without any actual commentary.

These "following" and "anticipating" are not intentional actions, but the result of a direct relationship between adult and child that occurs on the basis of a strong prediction of actions. Previous studies have linked this to "anticipation" and intentional synthesis (Shvarts & Zagorianakos, 2016).

In the second series of the experiment, by observing the child's actions, the adult has the opportunity to join the action and maintain the child's joint attention. Joint attention has been shown to naturally emerge from joint action (Yu & Smith, 2017). In our case, the child draws a pattern and thus works together.

It has been experimentally confirmed that in the learning process, an adult "indirectly experiences the child's attempts to find a solution" (Kim & Mundy, 2012), which transforms their perceptual activity in order to predict the child's actions and exercise proactive control. However, the perceptual activity of an adult will be specifically organized with children with atypical development and typically developing children.

The facts of synchronicity of the perceptual actions of the dyad of an adult and a child in the learning process partially correspond to Vygotsky's idea of cooperation in the zone of proximal development, where the main actor is the child, and adults are sensitive and open to the child's strategies and are ready to adjust their own perception accordingly.

Conclusion

We used the synchronous eye-tracking technology to obtain eye-tracking data from adult-child dyads. For a comparative study of learning difficulties and detection of the specifics of the perceptual activity of the adult-child dyad, contrasting groups of typically developing children and children with hearing impairment were selected.

The DUET technology has yielded a display of perceptual actions of the dyads in a common visual space. On each of the videos of an adult and children from contrasting groups, a visualization of the spatial movement of the direction of gaze was made and the specifics of the perceptual actions of the dyad of an adult and preschoolers of two contrasting groups were analyzed.

Applying the construction of intersubjective connection between dynamic systems of perception and action, we paid special attention to the data that can come from:

1. Similarities and differences between the movements of the eyes of a child and an adult, since they enable the realization of real and ideal forms of eye movement and strategies of perception;

2. Coordination between the actions of the child and the perception of the adult. On the basis of the data obtained, it was possible to compare contrasting groups of preschoolers in terms of their models of the gaze direction route in a learning situation in order to identify the specifics of the establishment of episodes of joint attention, identified and visualized moments of impaired joint attention that impede effective learning of the child.

The applied DUET technology facilitated a display of the functioning of joint attention with an adult during learning in typically developing children and children with hearing impairment.

It is confirmed that teaching and learning are multimodal processes in which joint visual attention is established and maintained. Besides, a child's visual attention is established and maintained in learning or cooperation due to the adult's visual attention.

We were able to analyze the dynamics of joint attention in the flow of multimodal interaction and comprehend the organization of perceptual processes of the adult-child dyad during learning. Comparison of the dyads of an adult and a child in contrasting samples helped confirm the mutual transformation of the perceptual processes of both the adult and the child.

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