Automated Assessment of Eye-hand Coordination Skill using a Vertical Tracing Task on a Gaze-sensitive Human Computer Interaction Platform for children with Autism

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Children with Autism often demonstrate atypical gaze pattern and eye-hand coordination skill deficits marked by difficulties in reaching out for an object, tracing on a vertically mounted canvas, etc. Currently existing conventional methods can assess one's coordination skill during hand movement in 3D-space. But such methods can be subjective and devoid of gaze tracking. Investigation of coordination skill and gaze tracking of this target group in tasks set in 3D-space has been largely unexplored. To quantitatively assess one's eye-hand coordination skill, we have designed Virtual Reality-based Automated gaze-sensitive Tool that can help understand the linkage between their gaze and 3D performance. Results of a study with 10 pairs of age-matched children with Autism ($Group_{ASD}$) and typically developing children ($Group_{TD}$) showed that $Group_{ASD}$ demonstrated reduced eye-hand coordination skill (increased tracing error in vertical tracing task) accompanied with reduced fixation duration on task-relevant regions and atypical gaze path than $Group_{TD}$.

CCS Concepts: • **Education** • **Human Computer Interaction**

Additional Key Words and Phrases: Eye hand Coordination, Virtual Reality, Autism

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1 INTRODUCTION

Activities involving reaching out for an object, tying shoelaces, or manipulating fasteners (e.g., snaps, hooks), threading beads onto a string, painting or tracing on a vertically mounted canvas, etc. wherein one might need to move his/her hand in 3D space, require intact eye-hand coordination skill [1]. Intact eye-hand coordination skill combined with one's gross motor skills and visual functions allows us to perform many daily living activities [2]. Quantifying the Eye-Hand coordination skill may help understand how an individual uses tools, engages socially, etc. in daily living [3]. Deficits in such a skill, e.g., in children with Autism Spectrum Disorder (ASD) [4], [5] can adversely affect their ability to execute tasks of daily living, thereby emphasizing the importance of assessing their eye-hand coordination skill. Existing methods for assessing such deficits include tests such as the Bimanual Coordination task test [6], and Motor Coordination tests [7], Movement Assessment Battery for Children-Second Edition (MABC-2) [7], etc.

2573-0142/2024/05 – 224

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Although these tests are powerful, these are used to assess one's coordination skill in a task set in 2D space (requiring one's hand movement in the horizontal plane) with support from a drawing canvas and does not assess one's coordination skill in a task set in 3D space. Also, the assessment is based on the nature of the drawn output without any consideration of how the eye moves in tandem with one's hand movement. Added to one's hand movement in 3D space, an important ingredient of eye-hand coordination skill is one's gaze pattern during task execution [8] that needs to be monitored as well. This is particularly important for children with ASD who are often known to demonstrate atypical gaze pattern [9] (unlike their typically developing counterparts) that in turn can be linked with their deficits in eye-hand coordination skill [10] adversely affecting their performance such as in a task set in 3D space.

With the need to monitor one's gaze pattern during a task, researchers have explored gaze indices such as Fixation Duration (indicative of the dwell time dedicated to a given stimulus [11]), Fixation Counts (representing the number of times a region of interest has been fixated [12]), etc. during task execution [13], [14]. Although, such gaze indices of individuals with ASD have been explored for tasks, such as writing, drawing, etc. set in a 2D space, investigation of eye-hand coordination skill along with gaze tracking of children with ASD in tasks set in 3D space has largely remained as unexplored. Such investigation might help explain the underlying linkage, if any between the gaze pattern and task performance of this target group in a task requiring hand movement in 3D space along with their eye-hand coordination.

Based on the existing literature, we hypothesize that deficits in eye-hand coordination skill along with atypical gaze pattern of individuals with ASD adversely affect their performance in 3D curve tracing tasks. For this, we wanted to assess the eye-hand coordination skill of individuals with ASD in a task set in 3D space along with investigating their gaze pattern during the task execution. For this, in our present work we have designed a Human Computer Interaction platform that can help assess the eye-hand coordination skill (and task performance using an electromagnetic tracker) and monitor one's gaze pattern while participating in a vertical tracing task. Thus, the objectives of our current work were (i) to design a Virtual Reality-based Automated gaze-sensitive Tool (VRAT henceforth) for assessment of one's eye-hand coordination skill and quantification of gaze pattern in terms of Fixation Duration and Fixation Counts while executing a task and (ii) conduct a feasibility study involving two participant groups, namely children with ASD and their typically developing (TD) counterparts to (a) explore the differences in their eye-hand coordination skill using a performance index and (b) compare their gaze indices in terms of Fixation Duration and Fixation Counts towards specific region of interest of the visual stimulus along with their gaze paths during the execution of a vertical tracing task.

2 RELATED WORK

Children with ASD often show reduced eye-hand coordination skills [4] causing them to face challenges in performing handwriting and drawing tasks [15] These hamper their overall academic and social development [15]. Before proceeding with the assessment of the skill deficit of children with ASD, it is necessary to adopt appropriate tasks (as part of the assessment regime) for quantifying the performance. Here we describe some of the existing literature related to the currently-existing assessment regime of eye-hand coordination tasks, such as drawing tasks along with the need to monitor one's gaze during execution of such tasks.

Research suggests that different forms of writing or drawing are subject to various constraints and require hand movement in either horizontal or the vertical plane [16]. For example, drawing on a canvas in the vertical plane requires one to move his/her hand against gravity during task execution [16] and is thereby more challenging as compared to writing on a horizontal canvas. This is because, execution of such tasks will need one to use proximal motor function (the upper arm and the shoulder) with greater muscle contraction [16] in contrast to the use of distal motor function (fingers and wrist) as in case of writing on a horizontal canvas [16]. Considering these challenges, researchers have highlighted the importance of exploring such proximal tasks, such as drawing on a vertical canvas for children with ASD [17].

As a next step to the skill assessment, the output (drawn output) generated needs to be appropriately quantified. Although standard assessment techniques, such as Bimanual Coordination task test [6], and Motor Coordination tests [18] exist, these conventional techniques tend to be subjective in nature and also require trained manpower to assess the produced output. With advancement of technology in the field of robotics, image processing and Virtual Reality (VR), these alternatives to conventional techniques have been used by researchers to offer quantitative (non-subjective) assessment of such skill. For example, Grantner et al. (2005) have used a haptic robot along with fuzzy logic for automated assessment of the VR-based task performance [19]. Again, image processing techniques have been used by researchers for scoring a drawn output generated while participating in conventional assessment tests thereby alleviating subjectivity in the assessment [20]. Further, Junghans et al. (2019) have demonstrated the feasibility of using app-based eye-hand coordination test on a tablet which uses tracing error (error in produced trace compared to displayed template) to assess one's eye-hand coordination skill [21]. In another study, Rane et al. (2023) have used a VR-based platform integrated with electromagnetic tracker setup to compute one's task performance in terms of the tracing error in proximal and distal drawing tasks [22].

Although such studies have provided significant contribution to automated assessment of one's coordination skill in drawing tasks, none of these studies have considered the role of gaze in such tasks thereby missing on an important linkage in the eye-hand coordination skill, particularly important for individuals who are often reported to possess deficits in such skills, such as for individuals with ASD. In fact, the importance of gaze in tasks requiring intact eye-hand coordination skill, such as in a surgery task had been shown in a study by Harvey et al. for neurotypical adults. In this study, researchers have shown the importance of gaze fixation in deciding one's task performance [21]. Given the importance of gaze and the need to assess one's eye-hand coordination skill, such as in a task of drawing on a vertical canvas, further exploration of automated assessment techniques while incorporating gaze related metrices is warranted. Such automated assessment while looking to multiple aspects, such as gaze and eye-hand coordination can provide insights into specific deficits (of children with ASD) leading to their reduced task performance.

3 MATERIALS AND METHODS

3.1 Methodology

In our present work, we present our study in which we used a Virtual Reality-based Automated gaze-sensitive Tool (VRAT; Fig. 1 showing a bird's eye view) designed by us for the assessment of eye-hand coordination skill. This tool consisted of (i) Eye Tracker, (ii) Pen Tracker, (iii) Pen State and (iv) Task Presentation and Computation modules. The Eye Tracker module tracked the user's eyes and recorded time-stamped 2D gaze coordinates. The Pen Tracker module was used to measure the 3D coordinates of one's hand (projected in the VR environment as a virtual object, i.e., a VR_{Pen}). The Pen State module used the Pen state Data Acquisition (Pen $State_{DAQ}$) unit to communicate the states, namely ‘Pen-down’ or ‘Pen-up’ of VR_{Pen} to a Task Computer housing the Task Presentation and Computation module that presented the VR interface (i.e., the VR screen) for performing a vertical Curve-tracing task and computing the gaze and performance indices.

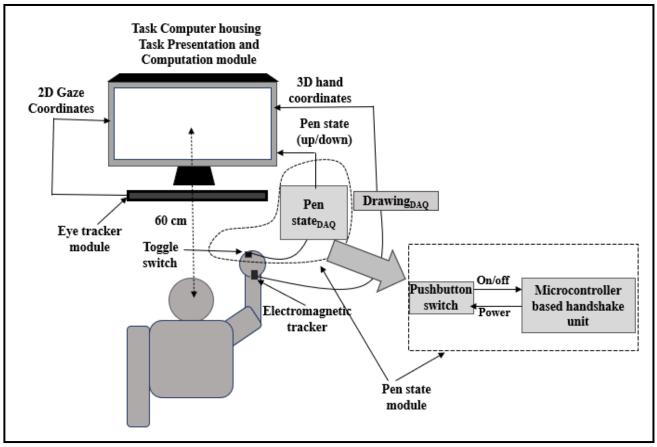
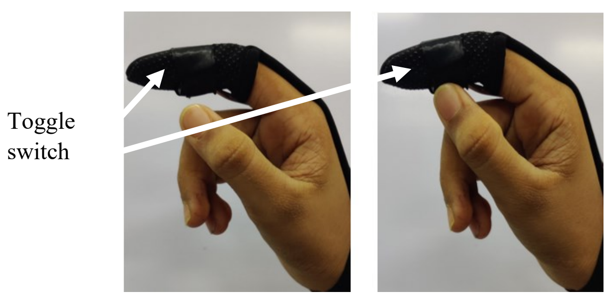


Figure 1: Bird’s Eye view of Virtual Reality-based Automated Gaze-sensitive Tool

3.2 Eye Tracker Module

We used Tobii 4c tracker (by Tobii LLC) as the Eye Tracker module that measured one’s 2D gaze coordinates at 90 Hz. The Tobii 4c tracker implements noise removal and offers the 2D gaze coordinates in a time-synchronized manner. The time-synchronized gaze coordinates representing one’s gaze location on a presented visual stimulus were stored in the Task Computer in backend. This data was subsequently used for computation of gaze indices (Section 3.10).



(a) (b)

Figure 2: Toggle switch of Pen-state module in (a) OFF or Pen-up state and (b) ON or Pen-down state

3.3 Pen Tracker Module

The Pen Tracker module consisted of an electromagnetic tracker (Fig. 1) that offered 3D coordinates of the one’s hand (holding the pen in the VR environment) in the physical space. The location of one’s hand (its 3D coordinates) in the physical environment were then transformed to 2D coordinates of the VR_{Pen}. The VR_{Pen} moved in the virtual environment based on the movement of the participant’s hand in the physical space as a projection of the user’s hand in the sagittal plane parallel to the screen without considering the horizontal distance of one's hand from the screen.

3.4 Pen State Module

The Pen State Module comprised of (i) a light-weight toggle switch unit housed in a fabric glove and (ii) Pen State$_{DAQ}$ unit. The Pen State$_{DAQ}$ unit consisted of a microcontroller unit that measured the state of the switch and transmitted it to the Task Computer via a USB cable. This module was used to simulate 'Pen-up' (Fig. 2 (a)) and 'Pen-down' (Fig. 2 (b)) states. When the switch was pressed (i.e., switch ON simulating the VR$_{Pen}$ touching the VR screen) then the VR$_{Pen}$ was considered to be in the 'Pen-down' state (i.e., can create a grey colored imprint on the VR screen. In contrast, when the switch was not pressed (i.e., switch OFF simulating the VR$_{Pen}$ as not touching the VR screen) then the VR$_{Pen}$ was considered to be in the 'Pen-up' state and was programmed not to create an imprint on the VR screen. Each 'Pen-down' state was used to add a dot of 8 pixels in diameter (decided based on a pilot study to ensure visibility of the created dot from a distance of 60 cm from the user) in real-time on the VR screen.

3.5 Task Presentation and Computation module

The Task Presentation and Computation module housed in the Task Computer consisted of the (i) Task Presenter unit and (ii) Index Extractor unit. The Task Presenter unit offered a VR

Table 1: Participant Characteristics

ID	Gender	Age (Years)	SRS (Cut-off=60)	SCQ (Cut-off=15)
		Group$_{ASD}$		
A1	M	7	64	20
A2	M	9	80	17
A3	M	8	64	17
A4	M	7	67	18
A5	M	6	72	16
A6	M	7	66	20
A7	M	8	74	16
A8	M	7	71	18
A9	M	8	68	22
A10	M	9	72	19
Mean (S.D)		7.6 (0.97)	69.8 (5.06)*	18.3 (1.94)*
		Group$_{TD}$		
T1	M	7	49	6
T2	M	9	42	2
T3	M	8	43	5
T4	M	8	48	6
T5	M	7	42	1
T6	M	7	42	1
T7	M	8	46	4
T8	M	8	39	5
T9	M	7	44	2
T10	M	9	51	5
Mean (S.D)		7.8 (0.79)	44.6 (3.78)*	3.7 (2.00)*

Note: * indicates pvalue<0.05 across the participant groups.

environment (developed using python-based Vizard software) with a vertical black colored sinusoidal curve of 570 pixels x 320 pixels (Reference Curve (Fig. 3)) presented against a white background. A 2D image of the Reference Curve was displayed along with the VRPen being

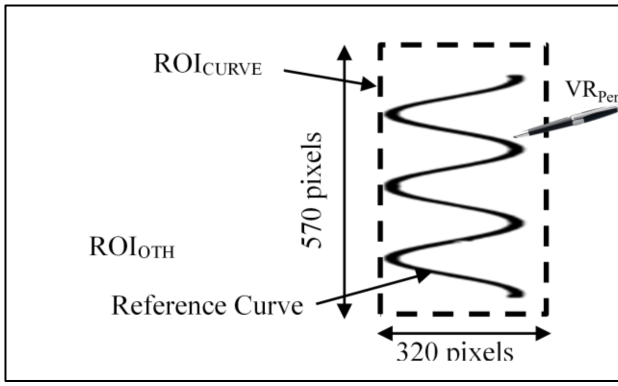


Figure 3: Visual Stimulus displayed on the VR screen

presented as a 2D image projected in a virtual 3D environment (Fig. 3). The Task Presenter was programed to present the Reference Curve on either side of the screen based on the preferred side (of tracing) of the user. The VR environment was divided into two Regions of interest (ROIs), namely ROI_{CURVE} and ROI_{OTHER} (Fig. 3). The ROI_{CURVE} corresponded to the Region of Interest enclosing the Reference Curve and the ROI_{OTHER} corresponded to the screen other than the ROI_{CURVE} (Fig. 3). The Index Extractor module was used to extract gaze-based and performance indices. With regard to the gaze-based indices, the Extractor module computed Average Fixation Duration [23] and Average Fixation Counts [12] (for details, please see Section 3.10) from the time-stamped 2D gaze coordinates recorded using the Eye Tracker module (Section 3.2). Again, with regard to the performance indices, the Extractor module computed the Tracing Offset (for details, please see Section 3.9).

3.6 Participants

We designed a feasibility study in which twenty participants (10 children with ASD ($Group_{ASD}$) and 10 Typically Developing children ($Group_{TD}$)) took part. The participants of both the groups had no motor deficits as reported by the therapists and caregivers in the case of $Group_{ASD}$ and by the teachers from the regular school in the case of $Group_{TD}$ where they were enrolled. The children belonging to the $Group_{ASD}$ were recruited from a neighboring Mental Health institute following therapist's recommendation. The children belonging to $Group_{TD}$ were recruited from a local regular school. Furthermore, Social Communication Questionnaire (SCQ) [24] and Social Responsiveness Scale (SRS) [25] and were administered to get an estimate of the autism score. The $Group_{ASD}$ was above the clinical threshold of 60 for SRS and 15 for SCQ unlike the $Group_{TD}$.

3.7 Experimental Setup

The setup (Fig. 4) comprised of (i) Task Computer, (ii) Eye Tracker module, (iii) Fabric glove with the Pen Tracker and Pen State modules, (iv) table and (v) chair in front of the Task Computer at a distance of nearly 60 cm. The Eye Tracker module (Tobii 4c) was a desktop mounted type of tracker and placed below the of the Task computer. The Fabric glove had the tracker (Pen Tracker unit) along with the toggle switch (of Pen State module) affixed on the distal phalange of the index finger of the preferred hand (as indicated by a user). The room was uniformly lit.

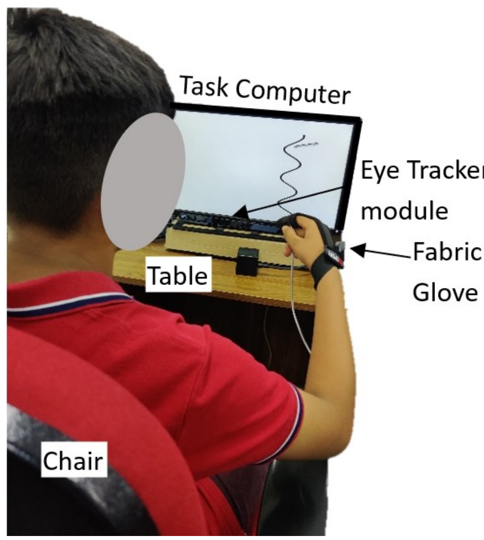


Figure 4: Experimental Setup

3.8 Procedure

Our present study required nearly 15 minutes of each participant's time. Upon the participant's arrival, the experimenter greeted the participant and asked him / her to sit comfortably on a height-adjustable chair placed in front and aligned with the center of the screen of the Task Computer, followed by introducing himself. Then the experimenter explained the task that the participant was expected to do using a visual schedule and showed the experimental setup. Also, the experimenter told the participant that a Reference Curve will be displayed to him on one side of the screen of the Task Computer. The task was to trace the Reference Curve (Fig. 3) with the palm of the hand kept in a neutral position (as shown in Fig. 2) and produce a Traced Curve by moving the hand in the physical space and in the air in front of the screen without touching the screen. Though execution of the task needed one to move hand in the air, we did not restrict the distance of one's hand from the screen (i.e., the depth information) while generating the image of the Traced Curve to allow one's free movement of hand in 3D space. Also, care was taken that with the participant being aligned with the center of the screen, the Reference Curve was not occluded by the participant's hand while the participant traced the curve. The experimenter handed over a fabric glove (similar to the one to be used in the study) to the participant for him / her to get used to the glove. Also, the participant was told that he/she was free to withdraw participation at any time and request for breaks during the task execution in case of any discomfort. This was followed by enquiring about the hand preference (i.e., the hand that the participant prefers) for drawing purpose. Once the participant understood what he was expected to do, the ethics signing (by the caregivers for $\text{Group}_{\text{ASD}}$ and by the teachers for Group_{TD}) was administered. The experimenter assisted the participant to wear the fabric glove having the Pen Tracker and Pen State modules. Then the participant was asked to take part in a practice session (with the 2D image of the Reference Curve displayed either towards the left or right half of the VR screen based on the hand (left or right) as preferred by the participant for drawing and the VR_{Pen} was presented as a 3D cursor) in which he could trace the Reference Curve. After the participant expressed that he was ready for the task, a 5-point calibration routine that comes with Tobii eye tracker was executed. Next, the task having 20 trials with the Reference Curve being displayed for 15 seconds for each trial either towards the left or right half of the VR screen based on the participant's preferred hand. The duration of each trail was chosen to be 15 seconds based on a pilot study wherein no time limits were imposed in the study design and individuals similar in age-group as that of the participants of our present study were found to be able to complete the task within the chosen trial duration. Given that the time limit of 15 s for completion of each trial was long enough to take care of the individual differences in the speed of tracing the curve based on our pilot study, we did not make the switching of trials sensitive to individual completion times. Once the participant started tracing the Reference Curve by moving his hand in a vertical plane (parallel to the sagittal plane) while closing the toggle switch of the Pen State module, the Traced Curve was displayed on the VR screen overlaying the Reference Curve in real-time. After the specified trial duration of 15 seconds, the Task Presentation and Computation module was used to refresh the VR screen and present the Reference Curve for the next trial. The study ended by thanking the participant. The study had received institutional ethics approval and was conducted in accordance with the Institute Ethics guidelines. A video of the task has also been provided as supplementary material.

3.9 Computation of Tracing Offset

While the participants drew the Traced Curve, the Extractor module computed one's performance and judged the eye-hand coordination skill in terms of the Tracing Offset i.e., the Euclidean distance between the Traced Curve and the Reference Curve. Before computing the Tracing Offset, the Task Presentation and Computation module preprocessed the recorded trace (obtained from the coordinates of the Traced Curve) while scaling and rotating the generated image (i.e., Traced Curve) to match the template (i.e., Reference Curve) and superimposition on the template image as described by Perner et al. [26] as shown in the Fig. 5. The 2D coordinates of the VR_{Pen} (reflecting the position of one's hand in 3D space in front and in a plane parallel to the screen irrespective of the depth, i.e., the distance of the hand from the screen) recorded in the 'Pen-down' state (Section 3.4) were used to generate an image of the Traced Curve in MATLAB [27]. The Euclidean distance of the 2D coordinates (x_{Trace}, y_{Trace}) of the pre-processed Traced Curve from the 2D coordinates (x_{Ref}, y_{Ref}) of the Reference Curve was computed and averaged over the number of trials (i.e., 20 trials as per our study design) using Eq. (1)

$$Tracing\ Offset_{AVG} = \frac{1}{Number\ of\ Trials} \times \sum_{j=1}^{Number\ of\ Trials} \sum_{i=1}^{N} \sqrt{\left(x_{Trace_{i,j}} - x_{Ref}\right)^2 + \left(y_{Trace_{i,j}} - y_{Ref}\right)^2} \tag{1}$$

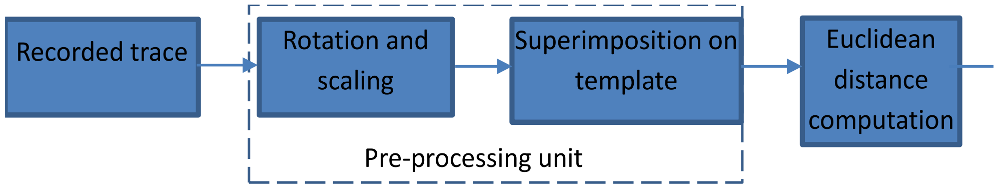


Figure 5: Tracking offset computation block diagram

Here N is the total number of pixels in the Traced Curve, and $x_{Trace_{i,j}}$, $y_{Trace_{i,j}}$ are the ith coordinates Traced Curve during the jth trial. While the Tracing Offset across all the trials varied between participants belonging to $\text{Group}_{\text{ASD}}$ and Group_{TD}, we normalized the Tracing Offset using min-max normalization [28] to compute $\text{Tracing Offset}_{\text{AVG-NORM}}$ (Eq. 2).

$$\text{Tracing Offset}_{\text{AVG-NORM}} = \frac{Tracing\ Offset_{AVG} - Tracing\ Offset_{AVG\_MIN}}{Tracing\ Offset_{MAX} - Tracing\ Offset_{AVG\_MIN}} \qquad (2)$$

Here $Tracing\ Offset_{AVG\_MIN}$ and $Tracing\ Offset_{AVG\_MAX}$ are the minimum and maximum $\text{Tracing Offset}_{\text{AVG}}$ obtained considering all the trials of all the participants.

3.10 Computation of Gaze Indices

While the participants looked towards the VR screen and performed the tracing task, the Eye Tracker module was used to capture one's gaze data that can offer important insights to one's eye-hand coordination skill [8] during the tracing task. Since, we were interested to investigate the eye-hand coordination during the 3D drawing task, we considered the time-stamped 2D gaze coordinates corresponding to the duration for which one's VR_{Pen} was in a 'pen-down' state marking the instants when the tracing of the curve was being done. The data on 2D gaze coordinates was preprocessed by the removal of the eye blink detecting the absence of data corresponding to the blink duration. Subsequently, this data was used by the Task Presentation and Computation module to compute gaze indices, namely Average normalized Fixation Duration and Average normalized Fixation Counts towards the different ROIs of the screen. With care being taken through the experimental setup such that the Reference Curve was not occluded by one's hand while one traced the curve, we ensured that the gaze coordinates being registered were those corresponding to one's viewing of the screen and not the hand that was moved in the air for tracing the curve.

3.11 Computation of Average Normalized Fixation Duration

The 2D gaze coordinates during each trial of the tracing task recorded during the 'pen-down' state was processed using the dispersion-threshold algorithm (for valid fixations) with a threshold of 100 msecs [29] and consecutive gaze coordinates lying within a bounding radius of 10 from the centroid of the gaze coordinates. The choice of the 100 msec threshold for accepted fixations [30] also helps in avoiding spurious fixations due to noise. Subsequently, the Fixation Duration for fixations lying within each ROI was summed up to get ROI-specific Total Fixation Duration (FD_{TOTAL}). Then, the Average Fixation Duration (FD_{AVG}) for each of $\text{ROI}_{\text{CURVE}}$ and $\text{ROI}_{\text{OTHER}}$ was computed using Eq. (3) from FD_{TOTAL} and Fixation Counts (Section 3.12).

$$FD_{AVG} = \frac{1}{20} \times \frac{1}{Fixation\ Counts} \times \sum_{i=1}^{20} \sum_{j=1}^{FixationCounts} FD_{TOTAL\ i,j} \quad (3),$$

Here i is the trial number and j is the index of fixation and $FD_{TOTALi,j}$ is the Fixation Duration of the jth fixation of the ith trial. While the overall FD_{AVG} across all the trials varied between participants belonging to $Group_{ASD}$ and $Group_{TD}$, we normalized the FD_{AVG} using min-max normalization to compute Average Normalized Fixation Duration ($FD_{AVG-NORM}$).

3.12 Computation of Average Normalized Fixation Count

The number of fixations of a participant during the 'pen-down' state was used to compute the Total Fixation Count. The number of Fixations lying within each ROI were summed up to get the Total Fixation Count (Fixation $Count_{TOTAL}$). Then, the Average Fixation Count (Fixation $Count_{AVG}$) for each of ROI_{CURVE} and ROI_{OTHER} was computed using Eq. (4).

$$Fixation\ Count_{AVG} = \frac{1}{20} \times \sum_{i=1}^{20} FixationCount_{TOTAL\ i} \quad (4)$$

Here i is the trial number and Fixation $Count_{TOTAL\ j}$ is the number of fixations counts of the ith trial. While the overall Fixation $Count_{AVG}$ varied between participants belonging to $Group_{ASD}$ and $Group_{TD}$, we normalized the Fixation $Count_{AVG}$ to get Average Normalized Fixation Count ($Count_{AVG-NORM}$) with values lying between 0 and 1 based on the maximum and minimum sum of fixation counts towards ROI_{CURVE} and ROI_{OTHER}.

3.13 Computation of Average Offset between Hand and Gaze Coordinates

In order to understand how one's eye moved in tandem with the hand while participants belonging to $Group_{TD}$ and $Group_{ASD}$ performed the tracing task, we computed the Euclidean distance between the Traced Curve and the gaze path plot. For this, the 2D gaze coordinates of the participants during the 'pen-down' state was used to generate the gaze path plot. Next, similar to the method used for computing the Tracing Offset (Section 3.9), the offset between one's hand and gaze coordinates i.e., Hand-Gaze offset was computed in terms of the Euclidean distance between the pixels in the gaze path plot and the Traced Curve. Subsequently, the Hand-Gaze offset was averaged across the 20 trials to obtain the Average Hand-Gaze offset (Hand-Gaze $offset_{AVG}$) for each participant belonging to $Group_{TD}$ and $Group_{ASD}$. While the Average Hand-Gaze offset varied between participants belonging to $Group_{ASD}$ and $Group_{TD}$, we normalized the Hand-Gaze offset to get Average normalized Hand-Gaze offset (Hand-Gaze $offset_{AVG-NORM}$) with values lying between 0 and 1 using on the Min-Max Normalization [28].

3.14 Computation of Spearman's Correlation

Additionally, in order to explore the linkage between the performance and the gaze index, the Spearman's correlation (Eq. 5) [31] between the $FD_{AVG-NORM}$ towards the ROI_{CURVE} and the Tracing $Offset_{AVG-NORM}$ was also computed. The Spearman's rank correlation is the Pearson's correlation of the rank values of the two variables [25] and is used assess monotonic relationships irrespective of whether or not they are linear (whereas the Pearson's correlation gives an estimate of the linear relationship between two variables) [25]. Hence to compute Spearman's rank correlation between two variables, the values of the two variables are assigned ranks, depending on the relative position of a value in the set of values taken by the variable. Next, the Pearson's correlation between these rank values (say Rx and Ry, as the ith rank values) is computed using Eq (3.3), where SD_{Rx} and SD_{Ry} are the standard deviations of Rx and Ry respectively.

$$r_s = \frac{cov(Rx,Ry)}{SD_{Rx} \times SD_{Rx}} \qquad (5)$$

3.15 Statistical Analysis

In order to perform comparative analysis of the gaze indices ($FD_{AVG\text{-}NORM}$ and Fixation $Count_{AVG\text{-}NORM}$) and the tracing performance (Tracing $Offset_{AVG\text{-}NORM}$), statistical significance tests were carried out. Since our sample size was limited for the preliminary feasibility study and the data was not normally distributed (as ascertained by Wilk-Shapiro test [32]), we carried out non-parametric tests. For comparing indices between $Group_{TD}$ and $Group_{ASD}$, we used the Mann–Whitney U test [32] and we used the Wilcoxon signed-rank test [33] for within group analysis.

4 RESULTS AND DISCUSSION

We wanted to evaluate the feasibility of VRAT system to assess the eye-hand coordination skill and quantify gaze pattern in terms of Fixation Duration and Fixation Counts of children with ASD (along with their difference from their typically developing counterparts) while executing a vertical tracing task. For this we conducted a feasibility study with children with ASD and their typically developing counterparts while we explored the differences in their eye-hand coordination skill using a performance index, namely Tracing Offset between the Reference Curve and Traced Curve. Also, we compared their gaze indices in terms of Average normalized Fixation Duration and Average normalized Fixation Counts towards specific region of interest of the VR screen followed by computing Average normalized Hand-Gaze offset. Additionally, we have looked at a case study by comparing the gaze paths of a participant with Autism and an age-matched typically developing participant.

4.1 Comparative analysis of Coordination Skill of GroupASD and GroupTD

All the participants were able to complete the tracing task in each trial within a duration of 10.1 (±1.6) s and 8.7 (±1.2) s for the $Group_{ASD}$ and $Group_{TD}$, respectively. While the participants traced the Reference Curve, our VRAT system computed the Tracing Offset in terms of the Euclidean distance (Eq. 1) between 2D coordinates of the pre-processed Traced Curve and the Reference Curve. The idea was to get an estimate of one's eye-hand coordination skill in terms of the Tracing Offset. It can be seen from Fig. 6 that the Average normalized Tracing Offset for the two participant groups were different with $Group_{TD}$ demonstrating statistically significantly lesser (p-value<0.001, U = 0, degree of freedom = 18, effect size = 9.5) Tracing $Offset_{AVG\text{-}NORM}$ than the $Group_{ASD}$. Such an observation suggests difficulties in tracing the Reference Curve faced by the $Group_{ASD}$ which might be due to reduced coordination skill than that of their typically developing counterparts that is in line with the findings from literature [1]. But, unlike previous study wherein the coordination skill of children with ASD was tested in response to hand movement in 2D space [34], in our study, we found reduced coordination skill of our participants with ASD in a task that needs movement of one's hand in 3D space. Possible reasons behind such reduced performance can be the deficit in the eye-hand coordination skill of the children with ASD along with their atypical viewing pattern [9].

4.2 Comparative analysis of Average Normalized Fixation Duration of $Group_{ASD}$ and $Group_{TD}$ in a 3D Vertical Tracing Task

Given that one's Fixation Duration on the stimulus while executing a coordination task, such as a tracing task can be a manifestation of one's atypical viewing pattern [9], we wanted to understand whether reduced performance quantified in terms of Tracing Offset can have any linkage with one's Average Fixation Duration on the ROI_{CURVE}. The Fig. 7 shows a comparative analysis of the Average normalized Fixation Duration ($FD_{AVG\text{-}NORM}$) on the ROI_{CURVE} and ROI_{OTHER} during execution of the tracing task by $Group_{TD}$ and $Group_{ASD}$. We found that the

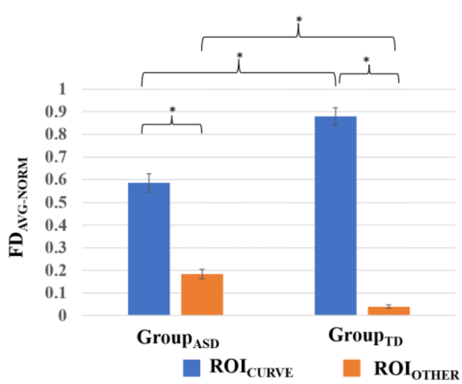


Figure 7: Comparative analysis of Group Average Normalized Fixation Duration ($FD_{AVG\text{-}NORM}$)
Note: *: p-value<0.05; $Group_{ASD}$ indicates children with Autism Spectrum Disorder; $Group_{TD}$ indicates typically developing children, y-axis represents normalized unit (normalized on a 0 to 1 scale).

$Group_{TD}$ had statistically greater $FD_{AVG\text{-}NORM}$ (p-value = 0.02, U = 20, degrees of freedom = 18, effect size = 7.2) towards the ROI_{CURVE} than the $Group_{ASD}$. In contrast, the $Group_{TD}$ had statistically lesser $FD_{AVG\text{-}NORM}$ (p-value = 0.002, U = 9, degrees of freedom = 18, effect size = 8.8) towards the ROI_{OTHER} than the $Group_{ASD}$ with the net $FD_{AVG\text{-}NORM}$ of $Group_{ASD}$ (considering both the ROIs) being lesser than that of the $Group_{TD}$ inferring that the $Group_{ASD}$ looked more outside the VR screen than the $Group_{TD}$ during task execution. In addition, considering within group statistical analysis, we found that the $FD_{AVG\text{-}NORM}$ towards the ROI_{CURVE} and ROI_{OTHER} were statistically different (p-value<0.01, W = 0, degree of freedom = 18, effect size > 10) within each of $Group_{ASD}$ and $Group_{TD}$. While considering the fixations towards the ROI_{CURVE}, the reduced $FD_{AVG\text{-}NORM}$ of $Group_{ASD}$ than the $Group_{TD}$ possibly helps in explaining at least one of the reasons behind reduced performance of the $Group_{ASD}$ as quantified in terms of higher Tracing $Offset_{AVG\text{-}NORM}$ (Section 3.9) than the $Group_{TD}$. In fact, while exploring the strength of the underlying linkage between the Fixation Duration and the respective performance, we found a correlation of nearly 0.93 (absolute) between the $FD_{AVG\text{-}NORM}$ and the Tracing $Offset_{AVG\text{-}NORM}$ for our participant pool.

4.3 Comparative analysis of Average Normalized Fixation Counts of $Group_{ASD}$ and $Group_{TD}$ in the 3D Vertical Tracing Task

With literature showing that good performers often demonstrate longer fixations coupled with reduced number of fixations on a target stimulus [22] and having seen that our $Group_{TD}$ demonstrated higher Average normalized Fixation Duration on the ROI_{CURVE} than that by the $Group_{ASD}$, we wanted to investigate whether there existed any difference in the Fixation $Counts_{AVG-NORM}$ (Section 3.10) between the two participant groups. It can be seen from the Fig. 8, that the $Group_{ASD}$ demonstrated greater Fixation $Counts_{AVG-NORM}$ towards both the ROI_{CURVE} and ROI_{OTHER} than the $Group_{TD}$ although the difference was not statistical (p-value = 0.07, U = 26,

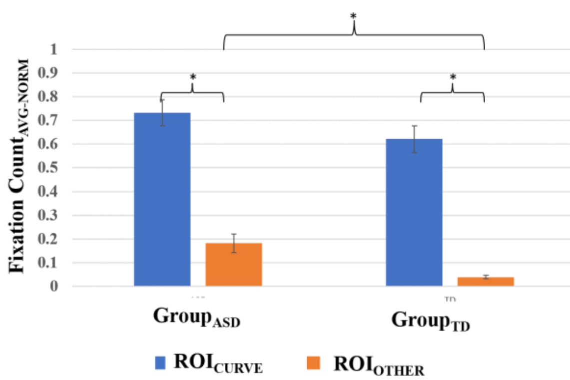


Figure 8: Comparative analysis of Group Average Normalized Fixation Count
Note: *: p-value<0.05; $Group_{ASD}$ indicates children with Autism Spectrum Disorder; $Group_{TD}$ indicates typically developing children, y-axis represents normalized unit (normalized on a 0 to 1 scale)

degree of freedom = 18, effect size = 2.8) for ROI_{CURVE} and was statistical (p-value<0.01, U = 14, degree of freedom = 18, effect size >10) for the RO_{IOTHER}. Moreover, for within group statistical analysis, both the groups demonstrated statistically (p-value<0.01, W = 0, degree of freedom = 18) greater Fixation $Counts_{AVG-NORM}$ towards the ROI_{CURVE} compared to ROI_{OTHER}.

4.4 Comparative analysis of Average Normalized Hand-Gaze Offset of $Group_{ASD}$ and $Group_{TD}$ in the 3D Vertical Tracing Task while considering Gaze Path Plot and Traced Curve

Having seen the differences in the gaze pattern and the disparity in the task performance in terms of Tracing Offset of the two participant groups during the vertical tracing task, we wanted to understand whether one's eye moved in tandem with the hand (movement) which might possibly help in investigating the underlying linkage in the eye-hand coordination and thereby explain the difference in task performance between $Group_{TD}$ and $Group_{ASD}$. For this, we have quantified the Euclidean distance between the gaze point of the participants from both $Group_{TD}$ and $Group_{ASD}$ and the tip of the VR_{Pen} creating the Traced curve in terms of Hand-Gaze offset (Section 3.11). It can be seen from Fig. 9 that the Average normalized Hand-Gaze offset for the two participant groups were different with $Group_{TD}$ demonstrating statistically significantly lesser (p-value<0.001, U = 0, degree of freedom = 18, effect size >10) Hand-Gaze offset than the $Group_{ASD}$. Such an observation suggests that the participants belonging to $Group_{ASD}$ had the VR_{Pen} (controlled by moving the hand) not closely following their gaze fixation path while performing the tracing task, unlike that of the participants belonging to $Group_{TD}$ which in turn might help explain reduced task performance in terms of greater Tracing Offset than their typically developing counterparts.

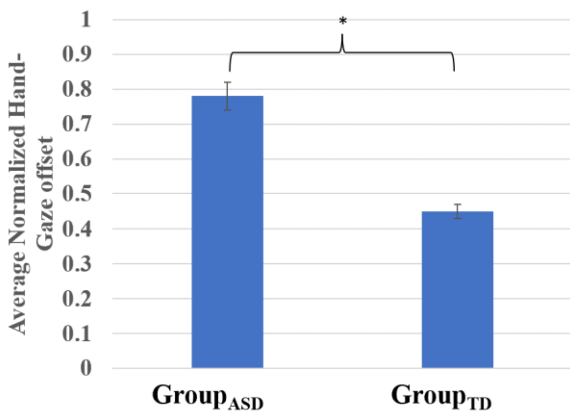


Figure 9: Comparative Group analysis of Average Normalized Hand-Gaze offset
Note: *: p-value<0.05, $\text{Group}_{\text{ASD}}$ indicates children with Autism Spectrum Disorder; Group_{TD} indicates typically developing children, y-axis represents normalized unit (normalized on a 0 to 1 scale)

4.5 Qualitative Representation of Gaze Path Plot and Tracing Output vis-à-vis Reference Curve of a Participant with ASD and a Typically Developing Participant

Having seen the quantitative differences in the gaze indices (with respect to the Fixation Durations and Fixation Counts) and the disparity in eye-hand coordination among Group_{TD} and $\text{Group}_{\text{ASD}}$ during the vertical tracing task, we wanted to further investigate how our participants with ASD differed from their typically developing counterparts in their gaze path capturing gaze behavior and in their tracing output with respect to the Reference Curve. Here, we offer a qualitative representation as an example of the gaze path plots (showing gaze during task

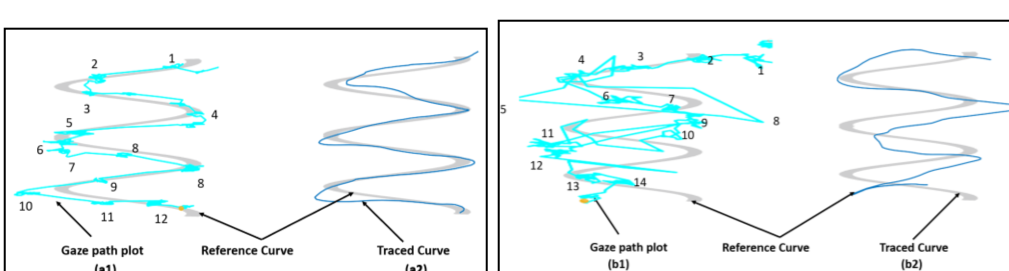


Figure 10: Comparative analysis of (a1) Gaze path plot of T6 (belonging to Group_{TD}), (a2) Traced Curve of T6, (b1) Gaze path plot of A6 (belonging to Group_{TD}), (b2) Traced Curve of A6.

execution) and Traced Curve (i.e., the Tracing output) of a pair of age-matched participants namely A6 and T6 (Table 1; chosen as an example case) from the two participant groups for a single trial, both being overlayed on the Reference Curve. On comparing the gaze path plots (formed from the 2D gaze coordinates) of both A6 and T6, as shown in Fig. 10, it can be said that their gaze behaviors were different. Specifically, T6 closely followed the Reference Curve with the Traced Curve being similar (with intermittent deviations) to the Reference Curve thereby reflecting comparatively better eye-hand coordination than that for A6. In fact, A6 had gaze points scattered all over the VR screen (visual stimulus) while intermittently following the Reference Curve along with greater deviations in the Traced Curve from the Reference Curve than that for T6. Such disparity in the gaze path plots of A6 and T6 possibly helps explain the difference in their Tracing Offset being 27.5% with the Offset being higher for A6 than that for T6.

5 CONCLUSION AND FUTURE WORK

In the current work, a Virtual Reality-based Automated gaze-sensitive Tool (VRAT) for assessment of one's eye-hand coordination skill and quantification of gaze pattern during a vertical tracing task was developed. Limited research (to the best of our knowledge) has gone towards developing an automated gaze-sensitive eye-hand coordination assessment platform especially in case of tasks set in 3D space. The VRAT offers a (non-immersive) VR platform for performing a vertical tracing task while simultaneously recording one's hand movement in the 3D space and gaze pattern. Additionally, our system quantifies one's performance in the tracing task based on the Tracing Offset and the gaze behavior based on the Fixation Duration and Fixation Counts. The contributions of our present work as evident from the results of a preliminary study with children with ASD and their typically developing counterparts set in the application space of fine motor performance in a VR-based setting show differences in the gaze indices (and thereby eye-hand coordination) of the two groups that accounts for the difference in their fine motor performance. Our analysis showed that the typically developing participants were able to perform the vertical tracing task more accurately (with lesser offset between the Traced Curve and the Reference Curve) than the participants with ASD. Moreover, there existed differences in the gaze indices (i.e., Fixation Duration and Fixation Counts) in the two groups with typically developing children showing fewer but longer fixations towards the relevant region of interest while performing the task than their counterparts with ASD. Though our results are promising, extended studies are warranted. The existing preliminary study was conducted with a few participants who interacted with a single task. In future, we plan to extend our study with a larger participant pool and include different types of VR based tasks thereby contributing to the generalizability and applicability of our study. Also, one's gaze-related physiological measures, such as pupillary dilation, blink rate, etc. during task execution can also be explored in future. Notwithstanding these limitations, we believe that the VRAT system can be a useful easy-to-use tool to assess one's eye-hand coordination skill. This can become a complementary tool in the hands of the therapists working with children with ASD, thereby helping them to modify their intervention strategies if needed.

REFERENCES

[1] A. P. Georgopoulos and S. Grillner, "Visuomotor coordination in reaching and locomotion," Science (1979), vol. 245, no. 4923, 1989, doi: 10.1126/science.2675307.

[2] R. A. Abrams, D. E. Meyer, and S. Kornblum, "Eye-Hand Coordination: Oculomotor Control in Rapid Aimed Limb Movements," J Exp Psychol Hum Percept Perform, vol. 16, no. 2, 1990, doi: 10.1037/0096-1523.16.2.248.

[3] Michael Xavier and Deepak Shendkar, "Effects of a systematic manipulative skills motor activity programme on the eye-hand coordination of children with autism spectrum disorder," Int J Physiol Nutr Phys Educ, vol. 3, no. 1, pp. 251–254, 2018.

[4] D. E. Lidstone and S. H. Mostofsky, "Moving Toward Understanding Autism: Visual-Motor Integration, Imitation, and Social Skill Development," Pediatr Neurol, vol. 122, 2021, doi: 10.1016/j.pediatrneurol.2021.06.010.

[5] M. B. Nebel et al., "Intrinsic visual-motor synchrony correlates with social deficits in autism," Biol Psychiatry, vol. 79, no. 8, 2016, doi: 10.1016/j.biopsych.2015.08.029.

[6] C. Caetano, "Development of Visuomotor Coordination in School-Age Children: The Bimanual Coordination Test," Dev Neuropsychol, vol. 11, no. 2, 1995, doi: 10.1080/87565649509540612.

[7] R. Capistrano, E. P. Ferrari, L. P. De Souza, T. S. Beltrame, and F. L. Cardoso, “Concurrent validation of the MABC-2 motor tests and MABC-2 checklist according to the developmental coordination disorder questionnaire-BR,” Motriz. Revista de Educacao Fisica, vol. 21, no. 1, 2015, doi: 10.1590/S1980-65742015000100013.
[8] S. Rentsch and M. K. Rand, “Eye-hand coordination during visuomotor adaptation with different rotation angles,” PLoS One, vol. 9, no. 10, 2014, doi: 10.1371/journal.pone.0109819.
[9] T. Nakano et al., “Atypical gaze patterns in children and adults with autism spectrum disorders dissociated from developmental changes in gaze behaviour,” in Proceedings of the Royal Society B: Biological Sciences, 2010. doi: 10.1098/rspb.2010.0587.
[10] C. M. Lee and J. Bo, “Visuomotor adaptation and its relationship with motor ability in children with and without autism spectrum disorder,” Hum Mov Sci, vol. 78, 2021, doi: 10.1016/j.humov.2021.102826.
[11] P. Vansteenkiste, G. Cardon, R. Philippaerts, and M. Lenoir, “Measuring dwell time percentage from head-mounted eye-tracking data – comparison of a frame-by-frame and a fixation-by-fixation analysis,” Ergonomics, vol. 58, no. 5, 2015, doi: 10.1080/00140139.2014.990524.
[12] Z. Bylinskii and M. A. Borkin, “Eye Fixation Metrics for Large Scale Analysis of Information Visualizations,” ETVIS Workshop on Eye Tracking and Visualization, 2015.
[13] A. Belardinelli, M. Y. Stepper, and M. V. Butz, “It’s in the eyes: Planning precise manual actions before execution,” J Vis, vol. 16, no. 1, 2016, doi: 10.1167/16.1.18.
[14] A. Kovari, J. Katona, and C. Costescu, “Quantitative analysis of relationship between visual attention and eye-hand coordination,” Acta Polytechnica Hungarica, vol. 17, no. 2, 2020, doi: 10.12700/APH.17.2.2020.2.5.
[15] C. T. Fuentes, S. H. Mostofsky, and A. J. Bastian, “Children with autism show specific handwriting impairments,” Neurology, vol. 73, no. 19, 2009, doi: 10.1212/WNL.0b013e3181c0d48c.
[16] S. Portnoy, L. Rosenberg, T. Alazraki, E. Elyakim, and J. Friedman, “Differences in muscle activity patterns and graphical product quality in children copying and tracing activities on horizontal or vertical surfaces,” Journal of Electromyography and Kinesiology, vol. 25, no. 3, 2015, doi: 10.1016/j.jelekin.2015.01.011.
[17] D. Rane, P. Verma, and U. Lahiri, How Good is your Drawing? Quantifying Graphomotor Skill Using a Portable Platform, vol. 13517 LNCS. 2022. doi: 10.1007/978-3-031-22131-6_31.
[18] K. Macy et al., “Beery-Buktenica Developmental Test of Visual-Motor Integration,” Encyclopedia of Autism Spectrum Disorders, pp. 400–404, 2013, doi: 10.1007/978-1-4419-1698-3_1886.
[19] J. L. Grantner, R. Gottipati, N. Pernalete, G. A. Fodor, and S. Edwards, “Intelligent decision support system for eye-hand coordination assessment,” in IEEE International Conference on Fuzzy Systems, 2005. doi: 10.1109/fuzzy.2005.1452368.
[20] Y. Li, J. Guo, and P. Yang, “Developing an Image-Based Deep Learning Framework for Automatic Scoring of the Pentagon Drawing Test,” Journal of Alzheimer’s Disease, vol. 85, no. 1, 2022, doi: 10.3233/jad-210714.
[21] B. M. Junghans and S. K. Khuu, “Populations norms for ‘sLURP’ - An iPad app for quantification of visuomotor coordination testing,” Front Neurosci, vol. 13, no. JUL, 2019, doi: 10.3389/fnins.2019.00711.
[22] J. Causer, A. Harvey, R. Snelgrove, G. Arsenault, and J. N. Vickers, “Quiet eye training improves surgical knot tying more than traditional technical training: A randomized controlled study,” Am J Surg, vol. 208, no. 2, pp. 171–177, Aug. 2014, doi: 10.1016/j.amjsurg.2013.12.042.
[23] D. Rane, P. Sharma, M. Singh, and U. Lahiri, “Virtual Reality Based Gaze-Sensitive Aiming Task Platform: Role of Attention Allocation in Task Performance for Individuals With Autism and Typically Developing Individuals,” IEEE Transactions on Neural Systems and Rehabilitation Engineering, vol. 31, 2023, doi: 10.1109/TNSRE.2023.3248126.
[24] H. Coon et al., “Genome-wide linkage using the social responsiveness Scale in Utah autism pedigrees,” Mol Autism, vol. 1, no. 1, 2010, doi: 10.1186/2040-2392-1-8.
[25] S. Chandler et al., “Validation of the Social Communication Questionnaire in a population cohort of children with autism spectrum disorders,” J Am Acad Child Adolesc Psychiatry, vol. 46, no. 10, 2007, doi: 10.1097/chi.0b013e31812f7d8d.
[26] P. Perner, “Determining the Similarity Between Two Arbitrary 2-D Shapes and Its Application to Biological Objects,” International Journal of Computer & Software Engineering, vol. 3, no. 2, 2018, doi: 10.15344/2456-4451/2018/139.
[27] “The MathWorks - MATLAB & SIMULINK,” IEEE Circuits and Systems Magazine, vol. 6, no. 4, 2008, doi: 10.1109/mcas.2006.264832.
[28] W. Li and Z. Liu, “A method of SVM with normalization in intrusion detection,” in Procedia Environmental Sciences, 2011. doi: 10.1016/j.proenv.2011.12.040.
[29] P. Blignaut, “Fixation identification: The optimum threshold for a dispersion algorithm,” Atten Percept Psychophys, vol. 71, no. 4, 2009, doi: 10.3758/APP.71.4.881.
[30] N. A. Farha, F. Al-Shargie, U. Tariq, and H. Al-Nashash, “Artifact Removal of Eye Tracking Data for the Assessment of Cognitive Vigilance Levels,” in International Conference on Advances in Biomedical Engineering, ICABME, 2021. doi: 10.1109/ICABME53305.2021.9604870.
[31] J. H. Zar, “Spearman Rank Correlation,” in Encyclopedia of Biostatistics, Wiley, 2005. doi: 10.1002/0470011815.b2a15150.
[32] J. D. Gibbons and S. Chakraborti, Nonparametric statistical inference. 2010. doi: 10.5005/jp/books/10313_14.
[33] H.-Y. Kim, “Statistical notes for clinical researchers: Nonparametric statistical methods: 1. Nonparametric methods for comparing two groups,” Restor Dent Endod, vol. 39, no. 3, 2014, doi: 10.5395/rde.2014.39.3.235.

[34] M. Roglic, V. Bobic, M. Djuric-Jovicic, M. Djordjevic, N. Dragasevic, and B. Nikolic, “Serious gaming based on Kinect technology for autistic children in Serbia,” in 2016 13th Symposium on Neural Networks and Applications, NEUREL 2016, 2016. doi: 10.1109/NEUREL.2016.7800105.

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