# Virtual Reality Based Gaze-Sensitive Aiming Task Platform: Role of Attention Allocation in Task Performance for Individuals With Autism and Typically Developing Individuals

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***Abstract*— Individuals with Autism Spectrum Disorder (ASD) often exhibit difficulty in movement preparation and allocating attention towards different Regions of Interest (ROIs) of a visual stimulus. Though research has alluded to differences in movement preparation for aiming tasks between individuals with ASD and typically developing (TD) individuals, there is limited evidence (true for near-aiming tasks) on the contribution of the window (i.e., time duration) of movement preparation (i.e., the planning window preceding movement initiation) on one's aiming performance. However, investigation of the contribution of this planning window on one's performance in far-aiming task remains as majorly unexplored. Again, often one's eye movement leads the initiation of hand movement (for task execution) indicating the importance of monitoring one's eye movement in the planning stage, critical for far-aiming task. Most of the studies (in conventional settings) examining the role of gaze behavior on aiming performance have involved TD individuals and only a few involving individuals with ASD. Here, we have designed Virtual Reality (VR)-based Gaze-sensitive far-aiming (dart throw) task and monitored the looking pattern of participants while they interacted with the task environment. We carried out a study with 40 participants (20 in each of ASD and TD groups) to understand how the participant groups differed in task performance and gaze fixation within the movement planning window. We observed difference in the scan path and last fixation within the movement planning window before triggering the release of the dart with relevance to task performance.**

***Index Terms*— Autism, far-aiming task, fixation duration, virtual reality.**

## I. Introduction

INDIVIDUALS with Autism Spectrum Disorder (ASD) often exhibit difficulty in planning movement [1] added to other deficits. Atypical movement preparation and execution can help explain many of the behaviors exhibited by these individuals [2]. For example, researchers have shown that in goal-directed aiming task having multiple targets, individuals with ASD are consistent in selecting the starting location as the midpoint, irrespective of the location of the target, unlike typically developing (TD) individuals who change their starting location while anticipating the specific target stimuli [1]. Moreover, one of the movement planning studies supports the finding that individuals with ASD have difficulty planning goal-directed movements [3] while taking longer time [4] and also making greater errors [4] during execution of aiming tasks. This might be related to the challenge experienced by individuals with ASD in preparing for and anticipating a complete action sequence [5] before initiating a task, unlike TD individuals. This is particularly true for a goal-directed aiming task that requires one's ability to focus attention and plan movements before initiating the task [6].

Although research has alluded to possible differences in movement preparation for aiming tasks between individuals with ASD and TD individuals, yet there is limited evidence on the contribution of the window of movement preparation (i.e., the planning window preceding the movement initiation) on one's task performance in an aiming task. Specifically, though the motor plan readiness level (that can have implication on one's task performance) is individual-specific, yet an overall U-shaped pattern in the planning window (closely approaching the minimal value from ∼350 to ∼450 msec followed by an increasing trend beyond ∼450 msec prior to movement initiation) with regard to the motor readiness level [7] has been reported. Again, researchers have reported that after one's readiness to act, there exists ∼350 msec time window before one's conscious intention to move (i.e., to initiate an action for executing a goal-directed task) [8]. The goal-directed task can be a near-aiming or a far-aiming [9] task. In the case of near-aiming tasks, such as reaching towards a target, researchers have discussed the importance of movement planning window [7]. In the case of such a task, one can employ corrective measures (i.e., error corrective phase) while moving an object from a start location to a target location that is not feasible in the case of a far-aiming task [8]

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(e.g., throwing of a dart, firing a gun, etc.). In fact, in the case of a far-aiming task, there is no scope of incorporating corrections and one's control on the object (being thrown, e.g., dart, bullet, etc.) is lost (indicating absence of error correction phase) post the object has been released [9]. This in turn emphasizes the importance of studying the planning window prior to the release of the object, particularly in the case of a far-aiming task. However, study of the role of such a planning window in a far-aiming task remains as majorly unexplored and thereby warrants further investigation.

Irrespective of the aiming task, one needs to initiate movement, such as movement of the hand and eyes for executing a task. Research shows that often one's eye movement leads the initiation of hand movement indicating the importance of monitoring eye movement during the planning stage (prior to initiating the execution of a task) [1]. Most of the currently-existing studies (set in conventional settings) examining the role of gaze behavior on aiming performance, have been with TD individuals and there exist a limited number of studies with children with developmental disorder [10], e.g., children with ASD [11] who often exhibit atypical viewing pattern [11] and greater variability in hand and eye movements than TD individuals while performing aiming tasks [1]. For example, researchers such as Glazebrook et al. [1] have studied the role of gaze of individuals with ASD while making aiming movements in a near-aiming task. But here the gaze behavior has been explored during the error correction phase and not during the planning window prior to task initiation. Additionally, allocation of gaze towards specific Regions of Interest (ROIs) during the planning window prior to task initiation is important. This is because information derived directly through fixation on a target (in the presented visual stimulus) is necessary for improved task performance [12]. Specifically, for far-aiming tasks, one's gaze behavior (in terms of the last fixation) towards a target has been reported to be critical in deciding his/her performance [8]. However, individuals with ASD displaying atypical gaze behavior [1], face difficulty in allocating attention towards target and non-target in the visual field [13].

Given the need to investigate the role of (a) planning window (before movement initiation) in a far-aiming task and (b) gaze (towards specific ROIs of the visual stimulus) behavior during the planning window on the aiming performance, particularly for individuals with atypical viewing pattern, in our present work, we have designed a Virtual Reality (VR) based Gaze-sensitive Aiming task ($VG_{DART}$) platform and monitored the looking pattern of a group of individuals with ASD and their TD counterparts while they interacted with this platform. In this, we offered a VR-based dart throw aiming task comprising of various trials set in a simulated far-aiming task environment (presented in VR). The task environment was segmented into different ROIs. One's dart throw attempt was considered as successful if the dart hit a target, else it was considered unsuccessful. Our objectives were to (i) design the $VG_{DART}$ platform, (ii) carry out a study to understand how individuals with ASD and their TD counterparts differ in task performance (in the aiming task)

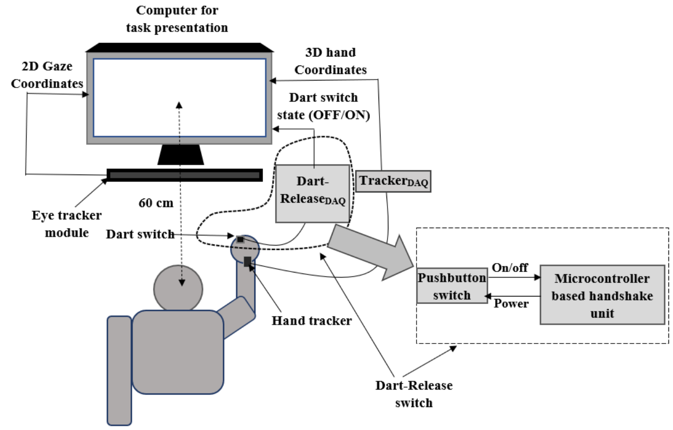



Fig. 1. Block diagram representation of our Virtual Reality dart throwing setup. Note: DAC represents data acquisition system.

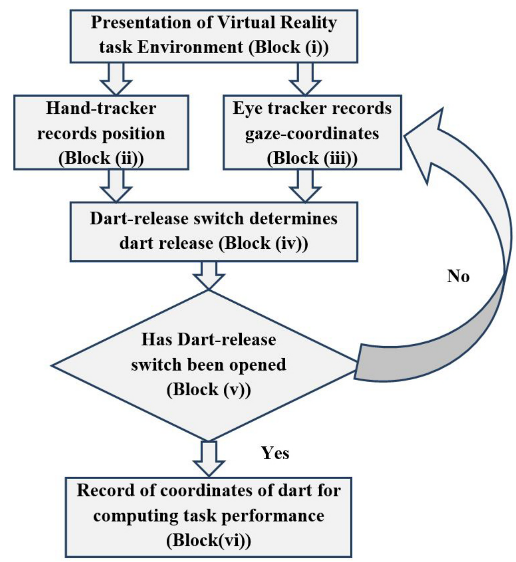



Fig. 2. Data Flow diagram.

quantified in terms of (a) overall distribution of successful and unsuccessful attempts, (b) group performance with task progression along with (c) performance error (closest the dart could reach a target) and (iii) investigate gaze fixation (towards different ROIs) within the movement planning window duration. In addition, we wanted to understand whether there existed any difference in the gaze pattern (within the movement planning window) of the participant groups in terms of (a) scan path and (b) last fixation point before triggering the release of the dart to understand their relevance to one's task performance in the VR-based aiming task through case study.

## II. System Design

Our VR-based gaze-sensitive dart (throwing) aiming task ($VG_{DART}$ *henceforth*) platform consisted of (i) Computer for Task Presentation, (ii) Dart-Release Switch Assembly, (iii) Hand tracker with Tracker Data Acquisition ($Tracker_{DAQ}$) and (iv) Eye tracker modules (Fig. 1). The modules were assembled to facilitate data transfer as shown in Fig. 2. The Computer was used to make the task presentation (Block (i) in

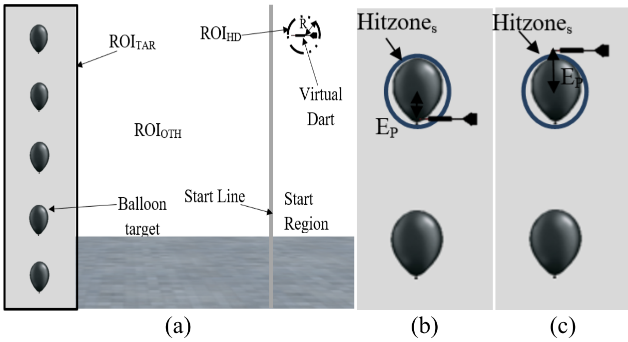



Fig. 3. (a) Visual display of VR environment segmented into different Regions of Interest (ROI), (b) successful attempt (dart strike inside $Hitzone_S$) (c) unsuccessful attempt (dart strike outside $Hitzone_S$ and with error Ep). Note: R = 1° eye angle = 40 pixels.

Fig. 2) by projecting a Graphical User Interface (designed in VR) of the aiming task on the monitor. The Hand tracker was used to register the 3D coordinates of one's hand (position) in the physical space (communicated via a data acquisition unit ($Tracker_{DAQ}$) to the Computer) that was mapped to the 2D coordinates of the dart in the VR environment (Block (ii) in Fig. 2). The Eye tracker module was used to record one's looking pattern through gaze coordinates (Block (iii) in Fig. 2). The Dart-Release Switch Assembly (comprising of a switch and the data acquisition unit ($Dart\text{-}Release_{DAQ}$)) was used to trigger the release (through switch being OFF) of the virtual dart and communicate the status (OFF / ON) of the switch to the Computer (Block (iv) in Fig. 2). Once the dart has been released (i.e., switch status being Opened (OFF state); Block (v) in Fig. 2), the $VG_{DART}$ recorded the 2D coordinates of the dart for computing task performance (Block (vi) in Fig. 2).

## A. Computer for Task Presentation

The Task Presentation module was used to present the Graphical User Interface (GUI *henceforth*) for the aiming task that was developed using Vizard software (from Worldviz Llc). The VR-based GUI (Fig. 3) was segmented into static and dynamic ROIs, namely for *Target* region ($ROI_{TAR}$ that was static), hand ($ROI_{HD}$ that was dynamic) and the rest of the monitor ($ROI_{OTH}$). The $ROI_{TAR}$ comprised of 5 black-colored balloons (of size ~60 × 60 pixels) placed vertically on a virtual wall displayed to the left or right side of the monitor of the Task Computer (based on the handedness of the user). For each balloon (*Target*), a circular region of (diameter =~ 60 pixels) from the center of the balloon) was used to specify the hit-zone ($Hitzone_s$ i.e., the zone of strike by the dart (being thrown with the throw being triggered by the Dart-Release Switch Assembly (described below)) for success in an aiming attempt. Once thrown, the dart was programmed to land on the virtual wall (with the landing point being related to the instantaneous position of one's hand releasing the dart, as indicated by the Hand tracker (Fig. 1) and defined with the dynamic $ROI_{HD}$). Once, a dart struck any point of the region within the $Hitzone_s$, the corresponding balloon was programmed to disappear and $VG_{DART}$ platform recorded the attempt as 'Successful' (along with computing the Task-related Performance Index (described in Section III-D.2)). Else, the attempt was registered as 'Unsuccessful'. Additionally, each $Hitzone_s$ were spaced ~120 pixels away from the neighboring $Hitzone_S$. Please note that these dimensions were decided based on a pilot study. The virtual dart ($ROI_{HD}$ being circle of diameter ~40 pixels with the dart at its center) was initially set to appear in the Start Region (Fig. 3). The Start Line (Fig. 3) was positioned 2.37 m (in the VR space) away from the virtual wall (like that in conventional dart throw setting [14]).

## B. Dart-Release Switch Assembly

The Dart-Release Switch Assembly was used to detect the opening of one's hand that simulated the release of the dart in the VR environment. It comprised of (i) a lightweight (6.0 × 6.0×5.0mm in size) pushbutton switch (Single Pole Single Throw type and mounted on the distal edge of the index finger of a fabric glove (single finger type) facing the palmar side) and (ii) $Dart\text{-}Release_{DAQ}$ (a microcontroller-based Data acquisition unit; Fig. 1). The pushbutton switch was wired to a $Dart\text{-}Release_{DAQ}$ that was programed to transmit the state (ON (i.e., '1') or OFF (i.e., '0')) of the switch to the Task Computer via a USB. The OFF-to-ON transition of the switch (in physical space) was used to trigger the release of the virtual dart. The pushbutton used in our study was chosen based on a pilot study.

## C. Hand Tracker With Tracker Data Acquisition Module

The Hand tracker with the data acquisition module was used to record the 3D position of the hand (holding the virtual dart) in the physical space. It consisted of Fastrak electromagnetic tracker (from Polhemus Fastrak™; accuracy=0.38 mm) with a lightweight receiver unit (12×10×10 mm in size) and a transmitter unit (defining the origin of the mapped physical workspace). The transmitter and the receiver units were connected to the Task Computer via a data acquisition unit ($Tracker_{DAQ}$ (Fig. 1) that comes with the Polhemus tracker) at a sampling rate of 120 Hz. Based on the position of one's hand in the physical space, the 3D coordinates of the tracker receiver were transformed to the 2D coordinates (x, y) specifying the position of the dart in the virtual environment. This data was stored in the backend of the Task Computer with time-stamping.

## D. Eye Tracker Module

The Eye tracker module was used to track one's eye movement, particularly before releasing the dart since we were interested in the looking pattern before the release of the dart. It consisted of a desktop-mounted Tobii 4c eye tracker (from Tobii AB) connected to the Task Computer via a USB 3.0 port. The eye tracker was used to acquire one's gaze data at a sampling rate of 90 Hz. The eye-gaze data comprised of time-stamped 2D (x, y) gaze coordinates (normalized on a 0 – 1 scale). This data was stored in the backend of the Task Computer and processed using our in-house built algorithm to extract one's Gaze-related Performance Index (described in Section III-D.1 below) corresponding to the different ROIs (Section II-A).

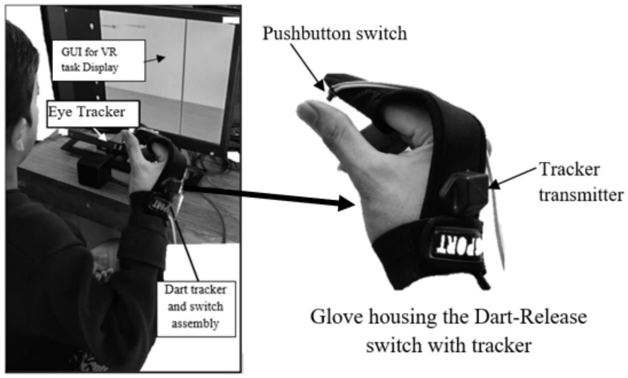



Fig. 4. Experimental Setup.

TABLE I
PARTICIPANT CHARACTERISTICS

| $Group_{ASD}$ | | | | $Group_{TD}$ | | | |
|---|---|---|---|---|---|---|---|
| ID (Gender) | Age (Years) | SRS (1) | SCQ (2) | ID (Gender) | Age (Years) | SRS (1) | SCQ (2) |
| ASD1 (M) | 14 | 65 | 15 | TD1 (M) | 5 | 43 | 5 |
| ASD2 (M) | 5.5 | 60 | 16 | TD2 (M) | 9 | 59 | 10 |
| ASD3 (M) | 11 | NA | 16 | TD3 (M) | 7 | 42 | 1 |
| ASD4 (M) | 10 | 63 | 16 | TD4 (M) | 7 | 38 | 2 |
| ASD5 (M) | 9 | 80 | 17 | TD5 (M) | 8 | 42 | 1 |
| ASD6 (M) | 9 | 64 | 17 | TD6 (M) | 8 | 44 | 2 |
| ASD7 (M) | 6.4 | 65 | NA | TD7 (F) | 10 | 59 | 9 |
| ASD8 (M) | 3.5 | 64 | 20 | TD8 (M) | 5 | 57 | 9 |
| ASD9 (M) | 5 | 67 | 18 | TD9 (M) | 9 | 48 | 7 |
| ASD10 (F) | 8 | 67 | 12 | TD10 (M) | 12 | 42 | 4 |
| ASD11 (M) | 6.5 | 66 | 20 | TD11 (M) | 9 | 56 | 12 |
| ASD12 (F) | 4 | 78 | 14 | TD12 (M) | 5 | 58 | 12 |
| ASD13 (F) | 9 | 75 | 20 | TD13 (F) | 8 | 42 | 1 |
| ASD14 (M) | 7 | 67 | 19 | TD14 (M) | 7 | 42 | 1 |
| ASD15 (M) | 4.5 | 71 | 9 | TD15 (M) | 7 | 40 | 4 |
| ASD16 (M) | 10 | 84 | 18 | TD16 (M) | 6 | 42 | 1 |
| ASD17 (F) | 9 | 76 | 19 | TD17 (M) | 8 | 42 | 1 |
| ASD18 (F) | 4 | 73 | 17 | TD18 (F) | 7 | 44 | 4 |
| ASD19 (F) | 5.4 | 90 | 27 | TD19 (M) | 9 | 42 | 2 |
| ASD20 (F) | 7 | 90 | 22 | TD20 (F) | 11 | 46 | 5 |
| Mean (S.D.) | 7.39 (2.7) | 71.8 (9.06) | 17.7 (3.87) | Mean (S.D.) | 7.85 (1.89) | 46.4 (7.06) | 4.65 (3.85) |

Note: $Group_{ASD}$: high-functioning individuals with ASD, $Group_{TD}$: Typically developing individuals, SRS: Social Responsiveness Scale, SCQ: Social Communication Questionnaire

## III. Experimental Setup and Procedure

### A. Experimental Setup

The experimental setup (Fig. 4) comprised of (a) Task Computer, (b) Dart-Release Switch Assembly, (c) Hand tracker unit, (d) Eye tracker, (e) a table and (f) a chair (with hand rests) facing the Task Computer (distance ~ 60 cm.). The Dart-Release Switch Assembly had a pushbutton switch attached to a fabric glove (single finger type) and it was wired to the $\text{Dart-Release}_{DAQ}$. The receiver of the Hand tracker unit was attached to the wrist of the fabric glove and kept on the table (carrying the Task Computer along with the $Tracker_{DAQ}$), respectively. The Eye tracker was placed on the table below the Task Computer. The study room was uniformly lit. The study protocol was reviewed and approved by the institutional ethics committee (No. IEC/2014-15/01/UL/002).

### B. Participant

Our study had the participation from 40 individuals, of which 20 were high-functioning individuals with ASD ($Group_{ASD}$ *henceforth*) and 20 were age-matched (p-value>0.05; for statistical tests used, please see Section III-E) TD individuals ($Group_{TD}$ *henceforth*) (Table I). The participants belonging to $Group_{ASD}$ were recruited from a local mental health institute based on therapist's referral and the participants of $Group_{TD}$ were recruited from a nearby regular school. The inclusion/exclusion criteria were (1) age between 5 and 15 years, (2) able to understand instructions, (3) without any motor deficit, (4) not use any spectacles and (5) have not undergone any eye-related surgery in the recent past. Table I shows the participants' characteristics. The participants belonging to $Group_{ASD}$ were above the clinical thresholds of either or both the Social Responsiveness Scale (SRS) [15] and Social Communication Questionnaire (SCQ) [16] measures. In contrast, all the participants belonging to $Group_{TD}$ had SRS and SCQ scores below the clinical thresholds with statistical difference (p-value<0.05) between the SRS and SCQ scores of the two participant groups.

### C. Procedure

Our study needed a commitment of ~30 minutes from each participant. Once the participant entered the study room, the experimenter introduced himself and he/she was asked to sit and relax. Following this, the experimenter tried to make the participant feel comfortable by having a casual discussion. Then, the experimenter showed the experimental setup to the participant, gave a demonstration on how to perform the task and instructed the participant to initiate the dart throw by triggering the release of the pushbutton switch (of the Dart-Release Switch Assembly) when the virtual dart was inside the Start Region (Fig. 3) for an attempt to be valid. This initial session took ~10 minutes. Once the participant expressed willingness to take part in the task, his/her caregiver was asked to sign the consent form. Also, the participant was informed that he/she was free to withdraw from the study at any point in case of any discomfort. In addition, the participant was told that he/she can ask for intermediate breaks while executing the task. Once the participant expressed that he/she was ready to start the task, the experimenter proceeded to perform the 5-point calibration for the Eye tracker (by executing the calibration software that comes with the Tobii Eye tracker). After this, the experimenter helped the participant to wear the fabric glove (having the Hand tracker and the Dart-Release Switch Assembly). This was followed by the participant executing the VR-based dart (throwing) aiming task. The $VG_{DART}$ platform offered twenty trials (of 10 seconds each and displaying a set of five balloons (*Targets* (Fig. 1))) during which the participant could make attempts (with no restriction on the number of attempts allowed). During an attempt, if the participant's dart reached any of the balloons (on the virtual wall) that is landed into the $Hitzone_S$ (Fig. 3)) of any of the balloons, the balloon was programed to disappear. This was followed by a new dart appearing again in the Start Region (Fig. 3) depending on the position of the Hand tracker (mounted on the fabric glove) unit and this continued till the duration of 10 seconds (for each trial) was over. On task completion, a message "Well done you have completed the task. Thank you." was displayed on the Task Computer.

### D. Evaluation of Performance

While a participant interacted with $VG_{DART}$ platform, our system evaluated one's performance in terms of (a) Gaze-related and (b) Task-related Performance Indices. The Gaze-related Performance Index was related to Fixation Duration and the Task-related Performance Index was in terms of (i) number of 'Successful' and 'Unsuccessful' attempts, and (ii) the minimum distance between a dart (being thrown) and the center of any of the balloons (in the $ROI_{TAR}$; Fig. 3).

*1) Evaluation of Gaze-Related Performance Index:* While one interacted with the $VG_{DART}$ platform, our system acquired one's gaze information. We were interested to investigate one's gaze behavior during a window of ~350 msec prior to the release of the dart by the participant. This is because, literature indicates that a window of 350 msec prior to initiating a move for executing a task is an optimum duration for planning movements and any duration lesser or more than the optimum window can lead to reduced performance [3]. Thus, we first extracted one's gaze data (2D (x, y) coordinates) during a window of ~350 msec prior to the instant of one's release of the switch (of the Dart-Release Switch Assembly (Section II-B)) i.e., trigger the release of dart in each attempt. This data was used to compute one's fixation duration (FD) corresponding to (i) 'Successful' attempt, (ii) 'Unsuccessful' attempt, (iii) $ROI_{TAR}$, (iv) $ROI_{HD}$ and (v) $ROI_{OTH}$ and stored at the backend of the Task Computer along with time stamping. For this, we first extracted the valid fixations using the dispersion threshold algorithm that considers a fixation as valid if the total duration was greater than 100 msecs [17] and the set of consecutive gaze coordinates (i.e., a cluster defining the fixation) lied within a region of $1^0$ from the centroid of the cluster. The valid fixations were then used to compute the FD while considering the duration between the first and last fixation (with gaze coordinates) belonging to that cluster. Subsequently, we identified minimum FD ($FD_{Min}$) and maximum FD ($FD_{Max}$) among those obtained by all participants over all the trials and one's FD was normalized (on a 0 – 1 scale) with respect to the planning window duration to compute $FD_{Norm}$ using Eq. (1).

$$FD_{Norm} = \frac{FD - \mathrm{FD}_{Min}}{\mathrm{FD}_{Max} - \mathrm{FD}_{Min}} \quad (1)$$

*2) Evaluation of Task-Related Performance Index:* One's task-related performance was evaluated in terms of percentage of attempts being 'Successful' (i.e., virtual dart reaching the $Hitzone_S$ of any of the balloons; Fig. 3 (a)) using Eq. (2) and 'Unsuccessful' (i.e., virtual dart not reaching the $Hitzone_S$ of any of the balloons; Fig. 3 (b)) using Eq. (3).

$$\%Attempt_{Success} = \frac{Number\ of\ successful\ attempts \times 100}{Total\ number\ of\ attempts} \quad (2)$$

$$\%Attempt_{Unsuccess} = \frac{Number\ of\ unsuccessful\ attempts \times 100}{Total\ number\ of\ attempts} \quad (3)$$

In addition, one's task-related performance was evaluated in terms of Performance Error (Ep; Fig 3 b, c) irrespective of the attempt. For this, we computed the least possible Euclidean distance (using Eq. (4)) between the virtual dart (striking the virtual wall; say ($x_1$, $y_1$)) thrown by a participant and the center of any of the balloons (say ($x_2$, $y_i$), with i varying from 1 to 5).

$$Ep = \min(\sqrt{(x_1 - x_2)^2 + (y_1 - y_i)^2}) \quad (4)$$

Subsequently, we identified minimum $E_p$ ($E_{pMin}$) and maximum $E_p$ ($E_{pMax}$) among those obtained by all participants over all the trials and evaluated the normalized Performance Error ($Ep_{Norm}$) on 0-1 scale across all the participants (Eq. (5)).

$$E_{pNorm} = \frac{E_p - \mathrm{E}_{pMin}}{\mathrm{E}_{pMax} - \mathrm{E}_{pMin}} \quad (5)$$

### E. Statistical Analysis

We wanted to carry out comparative analysis of Gaze-related and Task-related Performance Indices across 'Successful' and 'Unsuccessful' attempts and across '$ROI_{TAR}$', '$ROI_{HD}$' and '$ROI_{OTH}$' within and between the participant groups ($Group_{ASD}$ and $Group_{TD}$). Also, we wanted to understand the statistical significance of age along with the SRS and SCQ scores of the participants. Since these were not normally distributed (using Shapiro-Wilk test [18]), we used non-parametric statistical tests. For between group analysis, we used Mann–Whitney U test [18] and for within group analysis, we used Wilcoxon signed-rank test [19]. These tests were carried out in SPSS software (version 20). Additionally, in order to compare the probabilities of the alternate hypothesis against the null hypothesis [20] we also performed Bayesian analysis on the results, namely Bayesian Mann–Whitney test for inter-group analysis and Bayesian Wilcoxon signed-rank for within group analysis and using Jasp software [21] and have reported the Bayes Factor in favor of the alternate hypothesis ($B_{10}$).

## IV. Results and Discussion

While our participants ($Group_{TD}$ and $Group_{ASD}$) took part in the aiming task offered by the $VG_{DART}$ platform, our system recorded time-stamped data from the Hand tracker, Dart-Release Switch Assembly and the Eye tracker to compute one's Task-related and Gaze-related Performance Indices. We wanted to understand how the $Group_{TD}$ and $Group_{ASD}$ differed in (i) task performance in the aiming task quantified in terms of (a) overall distribution of $\%Attempt_{Success}$ and $\%Attempt_{Unsuccess}$, (b) group performance for successful attempts with task progression along with (c) Performance error (Ep) of each group and (ii) gaze fixation (FD) within the movement planning window duration (Section III-D.1) towards different ROIs ($ROI_{TAR}$, $ROI_{HD}$ and $ROI_{OTH}$) corresponding to the successful and unsuccessful attempts. Going deeper, we wanted to investigate whether there existed any difference in the gaze pattern (within the movement planning window) of the participants belonging to $Group_{TD}$

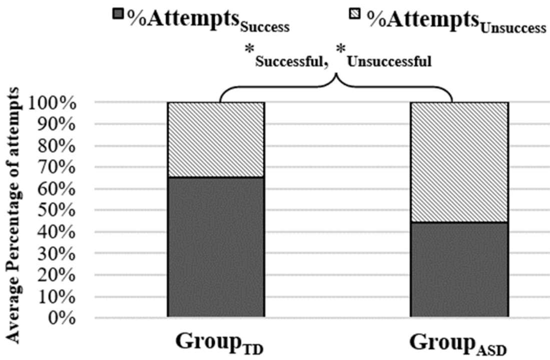



Fig. 5. Comparative analysis of percentage of successful and unsuccessful attempts among $Group_{TD}$ and $Group_{ASD}$. Note: $*_{Success}$, $*_{Unsuccess}$: p value $<0.05$ (for $\%Attempts_{Success}$ and $\%Attempts_{Unsuccess}$ respectively across $Group_{TD}$ and $Group_{ASD}$).

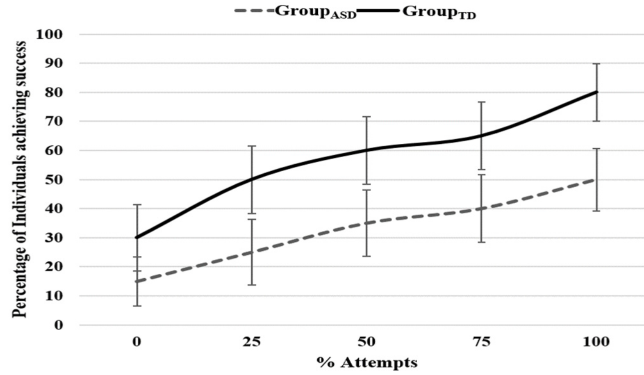



Fig. 6. Comparative analysis average successful and unsuccessful attempts among $Group_{TD}$ and $Group_{ASD}$ v/s percentage of attempts.

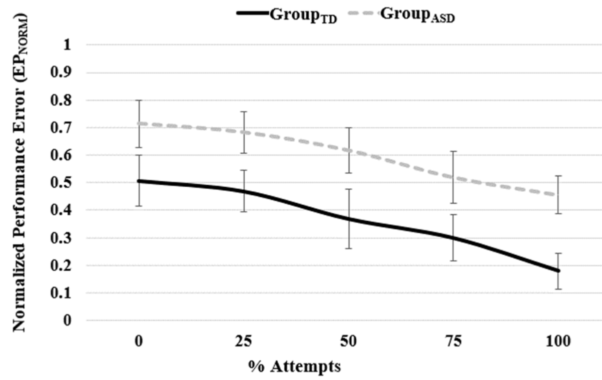



Fig. 7. Comparative analysis of performance error (distance from closest sub-target) v/s percentage of attempts for $Group_{ASD}$ and $Group_{TD}$.

and $Group_{ASD}$ in terms of (a) scan path and (b) distribution of last fixation on the three ROIs before triggering the release of the virtual dart to understand the relevance to one's task performance in the VR-based aiming task through case study.

## A. Comparative Group Analysis of Task-Related Performance Indices

We wanted to understand whether there existed any difference in the performance (quantified in terms of successful attempts (Section III-D.2) without penalizing for the unsuccessful attempts) of $Group_{TD}$ and $Group_{ASD}$ while they executed the VR-based aiming task. Also, we wanted to understand whether the percentage of participants (in each of $Group_{TD}$ and $Group_{ASD}$) who could make successful attempts with task progression, differed across the groups along with the Performance error.

*1) Distribution of Successful and Unsuccessful Attempts Across Participant Groups:* With regard to inter-group analysis, it was found that the group average $\%Attempt_{Success}$ (Fig. 5) of $Group_{TD}$ was statistically (p-value$<0.05$) greater ($\Delta\% = 20.6\%$) than that of $Group_{ASD}$ (who in turn had statistically (p-value$<0.05$, Bayes Factor $>100$ (suggesting extreme evidence for the alternate hypothesis)) higher ($\Delta\%=31.7\%$) number of unsuccessful attempts than that of $Group_{TD}$) inferring that the typically developing children (in our study group) were able to perform better than their age-matched counterparts with ASD in the aiming task. Such an observation on the difference in the aiming task performance between the two participants groups might indicate the possibility of the use of different attention allocation strategies, such as allocating attention towards different Regions of Interest (ROIs) causing them to miss *Target* while performing the task (among other factors), since the task performance might be related with how one allocates attention towards the task stimulus [22].

*2) Comparative Group Analysis of Trajectory of Percentage of Participants Making Successful Attempts as Task Progressed:* Having seen that the $Group_{ASD}$ and $Group_{TD}$ differed in terms of task performance (while considering all of the successful and unsuccessful attempts) in the aiming task, we wanted to understand whether the trajectory of the percentage of participants who could make successful attempts as the aiming task (having 20 trials with each trial having successful and/or unsuccessful attempts) progressed was similar across both the participant groups. With the number of attempts varying across participants, we normalized the number of attempts of each participant on a 0-100 scale and segregated that into five sub-sections, namely 0%, 25%, 50%, 75% and 100% of the attempts. Subsequently, we analyzed the percentage of participants in each of $Group_{ASD}$ and $Group_{TD}$ who could make successful attempts as the task progressed. It can be seen from the Fig. 6 that both $Group_{ASD}$ and $Group_{TD}$ demonstrated an increasing trend in the percentage of participants who could make successful attempts (using a spline fit [23] interpolation) as the task progressed. However, we see a greater improvement ($\sim$50%) in the percentage of participants who could achieve success from the first to the last attempts for the $Group_{TD}$ than that for the $Group_{ASD}$ ($\sim$35%) possibly due to faster acquisition of relevant attention allocation strategy (at least as one of the factors), such as allocating attention on the target leading to enhanced performance [22]. Again, lesser number of participants could achieve success in the first attempt than the subsequent attempts (true for both the participant groups) which might be possibly due to the novelty effect.

*3) Comparative Group Analysis of Variation in Normalized Performance Error as Task Progressed:* While we could see

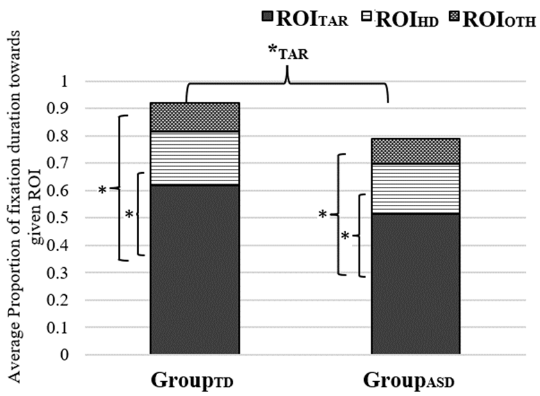



Fig. 8. Comparative group analysis of the distribution in fixation duration over $ROI_{TAR}$, $ROI_{HD}$ and $ROI_{OTH}$ for successful attempts. Note: $ROI_{TAR}$- *Target* ROI (Region Of Interest), $ROI_{HD}$ - Hand ROI, $ROI_{OTH}$ – Rest of the monitor. $*$: p-value<0.05 (for intra-group) and $*_{TAR}$:p-value<0.05 (inter-group for $ROI_{TAR}$).

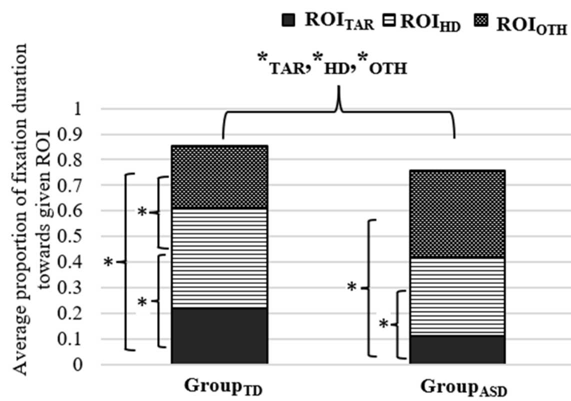



Fig. 9. Comparative group analysis of the distribution in fixation duration over $ROI_{TAR}$, $ROI_{HD}$ and $ROI_{OTH}$ for unsuccessful attempts. Note: $ROI_{TAR}$- Target ROI (Region Of Interest), $ROI_{HD}$ - Hand ROI and $ROI_{OTH}$ – Rest of the monitor. $*$: p-value<0.05 (for intra-group) and $*_{TAR}$:p-value<0.05 (inter-group for $ROI_{TAR}$), $*_{HD}$:p-value<0.05 (inter-group for $ROI_{HD}$), $*_{OTH}$:p-value<0.05 (inter-group for $ROI_{OTH}$).

that there was an increasing trend in the percentage of successful attempts from the first to the last attempts for both the groups (Section III-D.2), we wanted to understand how close the virtual dart was to any of the target balloons irrespective of the attempt. The Fig. 7 shows the variation in the normalized Ep ($Ep_{Norm}$; Eq. 5) as the aiming task progressed, i.e., with 0%, 25%, 50%, 75% and 100% of the attempts made (same as in Section IV-A.2) for $Group_{ASD}$ and $Group_{TD}$. We can see from the Fig. 7 that there was a decreasing trend in the average $Ep_{Norm}$ (using a spline fit [23] interpolation) for both $Group_{ASD}$ and $Group_{TD}$ as the task progressed. However, the decreasing trend in the $Ep_{Norm}$ from the first to the last attempts was steeper for $Group_{TD}$ ($\sim$ 0.31 normalized units) than that of $Group_{ASD}$ ($\sim$ 0.26 normalized units). Such an observation might be attributed to a variation in the attention allocation (towards the task stimulus) demonstrated by the $Group_{TD}$ and $Group_{ASD}$ (among other factors), since literature indicates attention allocation as one of the factors influencing one's performance [22].

### B. Comparative Group Analysis of Gaze-Related Performance Index

Given that attention allocation towards a task stimulus by an individual is one of the factors influencing one's performance while executing an aiming task [22], the importance of the optimal movement planning window ( [7]; Section II.D.1) before initiating movement for task execution along with the atypical gaze behavior [1] and difficulty in planning movements [1] often characterizing individuals with ASD unlike their typically developing counterparts, we wanted to understand whether there existed differences in the gaze fixation pattern in terms of $FD_{Norm}$ (Eq. (1) with regard to different ROIs ($ROI_{TAR}$, $ROI_{HD}$ and $ROI_{OTH}$ (Fig. 3)) during the movement planning window in the case of successful and unsuccessful attempts for $Group_{ASD}$ and $Group_{TD}$.

*1) For Successful Attempts:* It can be seen from Fig. 8 that both the participant groups had invested >50% of their respective optimal movement planning window in allocating attention towards the $ROI_{TAR}$ in attempts that had been successful. As far as the intra-group analysis is concerned, the $FD_{Norm}$ towards $ROI_{TAR}$ during successful attempts for $Group_{ASD}$ and $Group_{TD}$ were statistically (p- value<0.05, Bayes Factor >100 (suggesting extreme evidence for the alternate hypothesis)) higher than that towards $ROI_{HD}$ and $ROI_{OTH}$ ($\Delta\%$= 68.3%, 82.9%, respectively for $Group_{TD}$ and 64.3%, 82.0%, respectively for $Group_{ASD}$). This suggests that improved task performance (attempts leading to success) was related to one's greater fixation towards the target than towards non-target regions ($ROI_{HD}$ and $ROI_{OTH}$), irrespective of the participant group.

Again, with regard to the inter-group analysis, the $FD_{Norm}$ towards $ROI_{TAR}$ for $Group_{TD}$ was statistically (p-value<0.05, 3<Bayes Factor<10 (suggesting moderate evidence for the alternate hypothesis)) higher ($\Delta\%$=16.8%) than that of $Group_{ASD}$ implying that the $Group_{TD}$ invested more of their respective optimal movement planning window in fixating i.e., allocating attention towards the $ROI_{TAR}$ which possibly explains at least one of the reasons behind their ability to have more successful attempts (Section IV-A.1) and steeper reduction in the normalized performance error (Section IV-A.3) than that of their counterparts with ASD. In contrast, the $FD_{Norm}$ towards $ROI_{HD}$ and $ROI_{OTH}$ were nearly similar (p-value>0.05, 0.33<Bayes Factor<1 (suggesting anecdotal evidence for the null hypothesis)) between the two participant groups. In addition, the sum of the $FD_{Norm}$ towards the three ROIs for $Group_{ASD}$ was lesser than that of $Group_{TD}$ which can be due to the fact that the participants belonging to $Group_{ASD}$ were often shifting their gaze away from the monitor of the Task Computer (as reported by the experimenter) unlike the $Group_{TD}$.

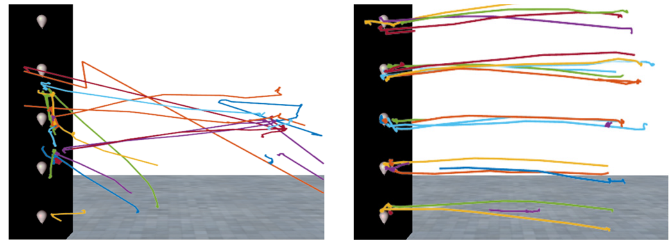
*2) For Unsuccessful Attempts:* For the unsuccessful attempts, we could see a different picture with regard to attention allocation towards $ROI_{TAR}$, $ROI_{HD}$ and $ROI_{OTH}$ from that for the successful attempts. In fact, for the attempts that were unsuccessful, the participants were fixating more towards either the $ROI_{HD}$ or $ROI_{OTH}$ than that towards the $ROI_{TAR}$, irrespective of the $Group_{ASD}$ and $Group_{TD}$ (Fig. 9).

In other words, the attempts leading to unsuccess had attention being allocated more to the non-target regions than the target, possibly causing the participants to miss the target. Specifically, with regard to intra-group analysis, the $FD_{Norm}$ towards $ROI_{TAR}$ for both the participant groups was statistically (p-value$<$0.05, Bayes Factor $>$100 (suggesting extreme evidence for the alternate hypothesis)) smaller than that towards $ROI_{HD}$ and $ROI_{OTH}$ ($\Delta$%=44%, 14.6%, respectively for $Group_{TD}$ and 63.5%, 66.7%, respectively for $Group_{ASD}$) for the unsuccessful attempts. Again, for $Group_{ASD}$, the $FD_{Norm}$ towards $ROI_{HD}$ and $ROI_{OTH}$ was nearly similar (p-value$>$0.05, 0.33$<$Bayes Factor$<$1 (suggesting anecdotal for null hypothesis)). However, for $Group_{TD}$, the $FD_{Norm}$ towards $ROI_{HD}$ was statistically (p-value$<$0.05, 3$<$Bayes Factor$<$10 (suggesting moderate evidence for the alternate hypothesis)) greater ($\Delta$%=36.7%) than that towards $ROI_{OTH}$ which might infer that they were allocating more of their attention towards the dart (before dart release) reflecting their own hand (holding the dart) position (that has been reported to lead to reduced performance [12], [24] during an aiming task) instead of towards $ROI_{TAR}$ with the attempt being unsuccessful.

Again, as far as the inter-group analysis is concerned, for the unsuccessful attempts, the $FD_{Norm}$ of $Group_{TD}$ towards the $ROI_{TAR}$ was statistically (p-value$<$0.05, 3$<$Bayes Factor$<$10 (suggesting moderate evidence for the alternate hypothesis)) greater ($\Delta$% = 48.6%) than that of $Group_{ASD}$ (Fig. 9), though the normalized fixation duration of $Group_{TD}$ towards the $ROI_{TAR}$ during the unsuccessful attempts was considerably less ($\Delta$%=64%) than that during successful attempts (Fig. 8). Again, with regard to the $ROI_{HD}$, for the unsuccessful attempts, the $FD_{Norm}$ of $Group_{TD}$ was statistically (p-value$<$0.05, 3$<$Bayes Factor$<$10 (suggesting moderate evidence for the alternate hypothesis)) greater ($\Delta$%= 23.0%) than that of $Group_{ASD}$ (Fig. 9). However, while considering the $Group_{TD}$, we find that this group spent considerably greater ($\Delta$%= 49.6%) time fixating towards the $ROI_{HD}$ during the unsuccessful attempts (which in turn might have led to reduced performance [22]) compared to that during successful attempts (Fig. 8 and 9). Finally, with respect to the $ROI_{OTH}$, for the unsuccessful attempts, the $FD_{Norm}$ of $Group_{ASD}$ was statistically (p-value$<$0.05, 3$<$Bayes Factor$<$10 (suggesting moderate evidence for the alternate hypothesis)) greater ($\Delta$%= 27.0%) than that of $Group_{TD}$ (Fig. 9) which might be due to the fact that the individuals with ASD often exhibit increased proneness to fixate on task-irrelevant ROI due to their obligatory processing of task-irrelevant stimuli [25].

### *C. Comparative Analysis of One's Gaze Pattern During the Movement Planning Window Duration: Case Studies*

Having seen the importance of one's attention allocation towards different ROIs of the presented task stimulus, we wanted to carry out in-depth exploration of how one's gaze pattern (during the Movement Planning Window duration [7]) varied in individuals with ASD and their TD counterparts in terms of (i) scan path across all the attempts and (ii) point of the last fixation before triggering the release of the virtual dart. This is because one's gaze pattern on a presented visual stimulus can be indicative of his/her scanning of the visual scene [26] that might have relevance to his/her task performance. Again, one's performance in an aiming task, such as dart throwing has been shown to be related to the last fixation towards the *Target* prior to the release of the dart [8], though such observation has been reported in case of dart throwing task set in a physical space (i.e., not in a virtual environment).



(a) (b)

Fig. 10. Scan path of (a) ASD14 and (b) TD14 during movement planning window duration prior to release of dart.

*1) Comparative Analysis of Scan Path of a Participant With ASD and TD Individual Across Attempts:* Although the gaze pattern (during the Movement Planning Window duration) varied across the participants, we could notice differences in the scan paths demonstrated by the participants belonging to $Group_{ASD}$ and $Group_{TD}$. Here we present the scan path (obtained by connecting the 2D eye gaze coordinates (x, y)) of successive fixation points of one such pair of age and gender-matched participants, namely ASD14 and TD14 (Table I) overlayed on the presented visual stimulus (as an example) as shown in the Fig 10. Subsequently, we computed the percentage of the total number of attempts made when a scan path (within the movement planning window prior to release of the dart) was registered between the first and last fixations made on the three ROIs. For example, if during a particular attempt, a participant fixated on the dart ($ROI_{HD}$) and then looked at one of the balloons ($ROI_{TAR}$) before releasing the dart, then this attempt was counted for the gaze being shifted between $ROI_{HD}$ and $ROI_{TAR}$. For ASD14, the scan path across all the attempts reflect that his gaze moved between the $ROI_{HD}$ and $ROI_{TAR}$ (i.e. shifted from either $ROI_{HD}$ to $ROI_{TAR}$ or vice versa), $ROI_{OTH}$ and $ROI_{TAR}$ (i.e. shifted from either $ROI_{OTH}$ to $ROI_{TAR}$ or vice versa), and $ROI_{OTH}$ and $ROI_{HD}$ (i.e. shifted from either $ROI_{OTH}$ to $ROI_{HD}$ or vice versa) for ~21%, 10.7% and 14.2% of the attempts, respectively (with the rest between $ROI_{HD}$, $ROI_{TAR}$, $ROI_{OTH}$ and outside the stimulus screen; and also, not moving gaze from a particular ROI) during the movement planning window duration. In contrast, for TD14, the scan paths (across attempts) were mostly between the $ROI_{HD}$ and $ROI_{TAR}$. Specifically, for TD14, the gaze moved between the $ROI_{HD}$ and $ROI_{TAR}$, $ROI_{OTH}$ and $ROI_{TAR}$, and $ROI_{OTH}$ and $ROI_{HD}$ for ~60.7 %, 10.7 % and 14.2 % of the attempts, respectively (with none between $ROI_{HD}$, $ROI_{TAR}$, $ROI_{OTH}$ and outside the stimulus screen; and rest not moving

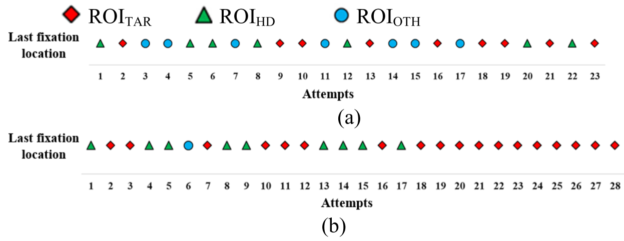



Fig. 11. Last fixation location of (a) ASD14 and (b) TD14 across attempts during movement planning window. Note: $ROI_{TAR}$ is target region of interest, $ROI_{HD}$ is hand holding dart region of interest and $ROI_{OTH}$ is other regions apart from $ROI_{TAR}$ and $ROI_{HD}$.

gaze from a particular ROI) during the Movement Planning Window duration.

Again, it can be seen from Fig. 10 (a) that out of the five target balloons, ASD14 was mostly shifting gaze between his hand (holding dart) and three of the targets while leaving the first and the last target (from the top). Also, irrespective of the target position, the hand position remained nearly at the midpoint. In contrast, it can be seen from Fig. 10 (b) that TD14 looked at all the target balloons and in turn his hand position also changed (based on the location of the target balloon). Such difference in the scan paths of ASD14 and TD14 during the Movement Planning Window duration is in line with observations on hand movement of TD individuals who change their starting location while anticipating the specific target stimuli and individuals with ASD are consistent in selecting the starting location as the midpoint, irrespective of the location of the target [1] in near-aiming task. This observation might explain the possible reason behind the variation in their task performance with 30% and 65% of the attempts being successful for ASD14 and TD14, respectively.

*2) Comparative Analysis of the Last Fixation Location Across Attempts of a Participant With ASD and TD Individual:* Since literature indicates that one's last fixation before initiating a far-aiming task is critical in deciding his/her performance [9] and that the gaze pattern of ASD14 and TD14 varied across attempts, we wanted to do in-depth exploration on whether their last fixation point (prior to releasing the dart) differed. For this, we analyzed the location of the last fixation (towards $ROI_{TAR}$, $ROI_{HD}$ and $ROI_{OTH}$) across attempts for ASD14 and TD14. It can be seen from Fig. 11 that for ASD14, the location of the last fixation switched frequently among the three ROIs across the attempts (with task progression). In contrast, for TD14, the location of his last fixation switched among the three ROIs only for the first ~60% of the attempts. However, his last fixation appeared to be towards the $ROI_{TAR}$ on the successively following attempts for the remaining attempts. Such an observation on the attention allocation [24] of TD14 might be possibly related to his better performance in the aiming task than that of ASD14.

## V. Conclusion and Future Work

In this work, we have developed a Virtual Reality (VR)-based Gaze-sensitive (dart throw) far-aiming task environment to understand the contribution of one's gaze behavior during a movement planning window on his / her aiming performance. Additionally, we conducted a study with typically developing (TD) individuals and those with Autism Spectrum Disorder (ASD) to understand the differences in the gaze behavior (within the Movement Planning window) between the two participant groups and whether such differences have relevance to the variation in their aiming performance. Our results indicate that there exist differences between their gaze behavior in terms of scan path and last fixation towards specific Regions of Interest (ROIs) of the task stimulus. The results suggest the importance of fixation (and hence attention allocation) towards the target (during the movement planning window immediately preceding the movement) for enhanced aiming performance. Although the results of our study are promising, there exist certain limitations. Here we have considered the movement planning window of 350 msec for all the participants while this can be individual-specific. In future, we plan to investigate the effect of using different lengths of planning window in our study and choose the one that leads to improved performance. Another limitation was that here we have used one type of far-aiming task, namely dart throw task simulated in VR. In future, we plan to design other aiming tasks (e.g., shooting task for a different far-aiming task and near-aiming tasks) in VR. Further, presently, we have simulated the far-aiming task in 2D VR and observed variations in gaze behavior within the simulated environment. In future, we plan to extend our study to the immersive VR environment and investigate the role of one's attention allocation in affecting one's aiming task performance.

Notwithstanding the limitations, our present work has contributed to a better understanding of the importance of monitoring one's attention during the movement planning window (preceding the movement initiation) and its importance in task performance in an aiming task. This can provide valuable inputs to therapists working with individuals with ASD who in turn can modify their intervention paradigm in an individualized manner suiting one's needs.

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