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Dynamic Eye gaze and its Potential in Virtual Reality Based Applications for Children with Autism Spectrum Disorders

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Abstract

Children with Autism Spectrum Disorder are often characterized by deficits in social communication skills. While evidence suggests that intensive individualized interventions can improve aspects of core deficits in Autism Spectrum Disorder, at present numerous potent barriers exist related to accessing and implementing such interventions. Researchers are increasingly employing technology to develop more accessible, quantifiable, and individualized intervention tools to address core vulnerabilities related to autism. The present study describes the development and preliminary application of a Virtual Reality technology aimed at facilitating improvements in social communication skills for adolescents with autism. We present preliminary data from the usability study of this technological application for six adolescents with autism and discuss potential future development and application of adaptive Virtual Reality technology within an intervention framework.

Keywords: Autism Spectrum Disorder; Virtual Reality; Eye-tracking; Fixation duration

Introduction

There is growing consensus that appropriately individualized intensive behavioral and educational interventions can improve core social communication vulnerabilities seen in individuals with autism spectrum disorder (ASD) [1,2]. However, there are potent barriers related to accessing and implementing appropriately individualized intensive intervention services such as limited access to and availability of appropriately trained professionals, lack of available data suggesting which interventions will work better for specific children, and exorbitant costs [3,4]. Further, while there are many promising interventions, there is also copious evidence suggesting that much vulnerability related to ASD show only moderate response to treatment and can be quite impairing throughout the lifecourse [5,6]. Given these barriers, researchers are increasingly employing technology to develop more accessible, quantifiable, individualized, and potentially more powerful interactive intervention tools [4]. More specifically, a growing number of studies are investigating applications of advanced interactive technologies (e.g., computer technology, robotic systems, and virtual reality environments) to social and communication related tasks for children with ASD [7-9].

Virtual reality (VR) technology possesses several strengths in terms of potential application for individuals with ASD, namely, malleability, controllability, replicability, modifiable sensory stimulation, and an ability to pragmatically individualize intervention approaches and reinforcement strategies [10]. While VR does not necessarily include direct human-to-human interaction, having controllable complexity of a virtual world with minimized distractions or distresses may allow for simplified but embodied social interaction that could be less intimidating or confusing for some individuals with ASD [11]. Recently Bellani et al. [12] has published a thorough state-of-the-art review on the applicability of VR in autism intervention [12] and concluded that since VR provides a simulation of the real world based on computer graphics, this can be useful as it allows instructors and therapists to offer a safe, repeatable and diversifiable environment during learning. In fact in this review the authors have presented the different VR based behavioral studies along with description of results achieved and also stated that the use of VR tools for habilitation in autism as very promising which may help caretakers and educators to enhance the daily life social behaviors of individuals with autism. VR can also illustrate and replicate scenarios which can be changed to accommodate various situations that may not be feasible in a given therapeutic setting [13]. Thus, VR represents a medium well-suited for creating and intensively studying the impact of interactive technological intervention paradigms for ASD.

Despite potential advantages, current VR environments as applied to tasks involving individuals with ASD are typically capable of modifying tasks based only on objective performance characteristics (i.e., correct or incorrect) of responses [9,14]. Though being able to adapt tasks based on performance is an important aspect of potential VR-based intervention systems, adaptation based solely on task performance limits the individualization of application and likely potential generalization of skills. Specifically, performance based VR-based interactions do not often involve measurements of or necessitate appropriate subtle, yet critically important, aspects of effective social communication (such as eye-gaze, and other forms of social convention). In fact, while many individuals with ASD are capable of yielding correct performance on objective task measures, it is their vulnerabilities surrounding elements of social communication that is so closely tied to their functional social impairments.

In the current work we focus on the development and initial application of a novel VR technology capable of incorporating real-time measurement and flexible adaptation to dynamic gaze patterns of adolescents with ASD in addition to objective task performance. Although an exhaustive review of the topic is beyond the scope of the current paper, it is a common finding

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that individuals with ASD often exhibit atypical gaze patterns during social interactions [15]. As such, a flexible technology designed to detect, respond to, and potentially enhance appropriate and socially modulated gaze as well as other more readily observed aspects of social interactions could be seen as a tool for potential enhanced ASD intervention. Emerging work in typically developing populations has researchers already demonstrated the feasibility of linking the gaze behavior of a virtual character with a human observer's gaze position during joint-attention tasks [16]. Extensions of VR-based gaze-sensitive applications to ASD population in a similar capacity may be an appropriate and realistic platform for creating more dynamic, individually responsive intervention technology. More specifically, enhanced VR-based system may be able to incorporate numerous data-sources (i.e., eye-gaze, eye physiological signals such as blink rate and pupil diameter, performance criteria) simultaneously in order to guide intelligent and automatic decisions used to bolster specific vulnerabilities related to ASD. In our previous report [17] we presented the technical details associated with the development of a novel VR- based social system integrated with computationally enhanced eye-tracking technology that could seamlessly integrate a VR platform with computationally enhanced eye-tracking to measure one's looking pattern and eye physiological indices in real-time during a VR-based social communication task.

In the present work, we demonstrate the feasibility of a technology integrating eye-tracking with VR with the potential of adaptive response. Specifically, we describe the development of a system that allows dynamic eye-tracking with VR interaction, such that the VR system pin-points quantitatively, where and how long a child is looking using metrics such as, fixation duration. Our initial report [17] presented the technical specifications of the developed system. In our present work, we provide additional data analysis results on variation of behavioral viewing indices such as, total fixation duration towards the face region of the avatars and object-to-face ratio (discussed in the section "Behavioral Viewing Indices derived from Gaze Data") of the participants across the different trials. In addition, we present data from the initial usability study employing a computational algorithm that utilizes these real-time quantitative metrics to provide individualized feedback based on gaze pattern and the performance of a participant in a social task to influence his/her behavioral viewing pattern. We fully recognize that developing a technology simply asking and reinforcing individuals with ASD to look toward a social target may be a limited enterprise and this is not the ultimate goal of the current study. Instead the current work represents a first-step in demonstrating the feasibility of a potentially more complex, sophisticated, and robust intervention system designed to detect patterns of gaze, as well as other subtle and necessary components of social communication. In this manner the current work demonstrates initial technological capacity to develop more robust and sophisticated technological systems that are capable of adjusting task characteristics in order to potentially modify and enhance aspects of social communication. We discuss potential expansions and applications of this technology based on the current work.

Materials and Methods

Participants

The objective of this work is to present the technological development of a new VR-based gaze-sensitive system, and to conduct a small usability study to determine how adolescents with ASD use the system (e.g., are they comfortable, etc.) and to observe whether the system can measure gaze parameters in real-time while the participants were involved in a VR-based task. For the usability study, six adolescents (Male: n = 5, Female: n = 1) with ASD, ages 13-17 (M=15.60 years, SD=1.27 years) participated in this study. All participants were recruited through existing clinical research programs at Vanderbilt University and had established clinical diagnoses of ASD. Participants were also required to score = 80 on the Peabody Picture Vocabulary Test-3rd Edition [18] to ensure that language understanding was adequate for participating in the current protocol. Data on core ASD related symptoms and functioning was obtained through parents' report on the Social Responsiveness Scale (SRS) [19] profile sheet and the Social Communication Questionnaire (SCQ) [20] with all participants falling above clinical risk thresholds (SRS total T-score: M=78, SD=11; SCQ total score: M=22, SD=7). Autism Diagnostic Observation Schedule (ADOS) scores were also available for 5 of the 6 participants from prior evaluation, with all 5 subjects falling in the clinical risk range (M=11, SD=5). All research procedures were approved by the Vanderbilt University Institutional Review Board. In the present study we did not include any control group of typically developing adolescents, since this study was meant to be a usability study to determine the functioning of the developed system. In the future, when the system will be used for intervention, a control population will be recruited.

Experimental Framework and Technology

Experimental setup included a 17" task computer monitor that was customized to present VR-based social communication tasks in the foreground and compute dynamic gaze information in the background. The VR experiment was created using the Vizard VR design package (from Worldviz Llc) and Arrington eye-tracker (from Arrington Research Inc). Our participants viewed the VR environment and avatars within the system from first-person perspective. Gaze data along with task-related event markers (e.g., trial start/stop, responses of participants to question asked by the system, etc.) were logged in a time-synchronized manner. Uniform room illumination was maintained throughout the experiment and sessions were video-recorded to afford the potential to cross-reference experimental observation.

Avatars, and Regions of Interest (ROIs) used

Three dimensional avatar heads were created from contemporary photographs of teenagers using the '3DmeNow' software package. These new avatar heads were used instead of pre-supplied Vizard creations, in order to create avatars: a) with age range close to our participant pool and b) with more authentic facial features (e.g., realistic brow line, nose dimensions, etc.). Neutral facial expression for the avatars (Figure 1) was

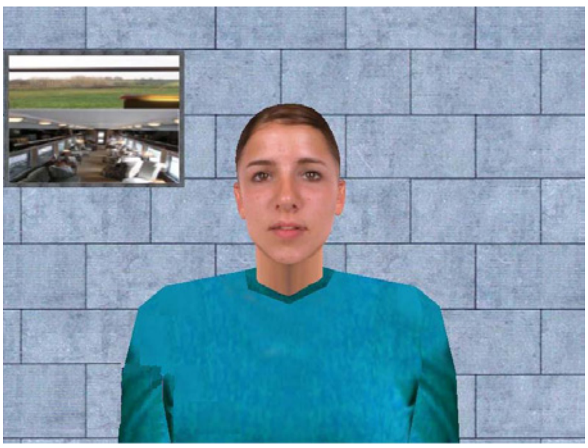

Figure 1: Allocation of ROIs (Face_ROI, Object_ROI, and Others_ROI).

embodied utilizing morphing as produced by 'PeopleMaker' software. After creation of these avatars we conducted field tests with undergraduate students in order to minimize potential reactions to the characters themselves [21]. The 5 most-neutral avatar heads from a sample of 26 heads based on a survey of 20 undergraduate students (M = 19.2, SD = 0.9) were incorporated into the current study.

Three regions of interest (ROIs) were analysed from acquired real-time gaze data within the VR environment: 1) the avatar's face (Face_ROI), a context-relevant object (Object_ROI), and the rest of the VR environment (Others_ROI) (Figure 1). Face_ROI captured the forehead, eye brows, eyes and surrounding muscles, nose, cheeks, mouth and surrounding muscles. Object_ROI captured a context-relevant object presented and narrated by the virtual character (i.e., a picture relevant to story told).

Behavioral Viewing Indices derived from Gaze Data

In this study, our aim was to capture the behavioral viewing patterns of the participants from their real-time gaze data. In dyadic communication, eye-gaze information underlying one's expressive behavior (i.e., amount of time a speaker and a listener look at each other) plays a vital role in regulating conversation flow, providing feedback, and avoiding distraction by restricting visual input [22]. In our experiment, each participant served as a listener. While the participant viewed the avatar narrating a personal story, the participant's viewing patterns were measured in real-time by acquiring gaze data and subsequently some behavioral viewing indices were computed.

An important indicator of behavioral viewing patterns is the Total Fixation Duration (FD Total), or simply the sum of the total time the participant was looking at a specific region of interest. Previous work has utilized varying intervals of fixation duration (FD) ranging from 100 milliseconds [23] to 600 milliseconds [24], with an interval of 200 milliseconds having been demonstrated to be robust to effects of blinking. In addition, the eye-tracker that we use provides a reliable data measurement range for fixation duration up to 450 milliseconds beyond which noise due to glare effects of the cameras of the eye-tracker sets in. As a result, in the present study, we compute the FD by using a minimal thresholding window of 200 milliseconds as the lower limit to eliminate the blinking effects and 450 milliseconds as the upper threshold in order to minimize effects of extraneous noise.

A new behavioral index that we introduce in this work is the Object-to-Face Ratio (OFR), which is defined as the FD for Object_ROI / FD for Face_ROI. OFR was created as a potential indicator of preference toward objects over faces and atypicality in visual shift related to faces and objects, effects that have previously been suggested in the existing literature [25]. As constructed, a decrease in OFR would imply that a participant is looking more towards the face region of an avatar as compared to a context-relevant object within the visual stimulus.

These two behavioral viewing indices, i.e., fixation duration (FD) and object-to-face ratio (OFR) were used in the present work to capture the viewing patterns of the participants during the task that we compute in real-time. Real-time gaze coordinates of a participant (interacting with an avatar) were acquired using Viewpoint software and converted to the VR compatible format using Vizard-Viewpoint interface module. Simultaneously a computer ranViewpoint Software at the background and Vizard software at the foreground and our developed algorithm triggered a 33 milliseconds timer to acquire the gaze coordinates. Subsequent to the data acquisition and processing (to eliminate noise and blinking effects), the algorithm then computed the specific ROI fixated by the participant along with the fixation duration. The times spent by the participant looking at the different ROIs were stored in the respective buffers, which were summed up at each instant while the participant listened and viewed the avatar narrating personal story for each trial. Subsequently the times corresponding to the Face_ROI, Object_ROI and Others_ROI were summed up to get the Total Fixation Duration. Then, the percentage of time spent by a participant in looking at Face_ROI was computed by the algorithm. Based on these computations and the participant's response to question asked by the system, feedback was provided by the system to the participants at preferred intervals about their viewing patterns during VR-based social tasks.

In order to observe the effect of this feedback, an experiment comprising of VR-based social communication tasks (5 trials) was designed. In each trial, first-person stories shared by avatars were adapted from fifth to sixth grade equivalents from the Dynamic Indicators of Basic Early Literacy Skills [26] reading assessments and included content thought to be related to potential topics of school presentations (e.g., reports on experiences, trips, favorite activities, etc.). At the end of each storytelling by an avatar, the participant was asked a story-related question, based on some basic facts of the narrated story. Subsequently, while the participant listened to the avatar's narration, based on the percentage of time spent by the participant for Face_ROI viewing and the participant's response to the story-related question, 4 different System Responses (S1-S4) (Table 1) were generated. We operationalised our appropriate 'normal while listening' gaze as a minimum of 70% as this ratio has been suggested in the social psychology literature [22,27] suitable for western culture [28].

Note that in this storytelling task, we did not want to interrupt the flow of narration by the avatar and thus chose to provide individualized feedback at the end of the each storytelling trial. However, the system is capable of providing feedback in real-time. For example, in a conversation task, feedback during the trial could be implemented.

Procedure

Each participant participated in an approximately 50 minutes laboratory visit. During this visit, the participant sat comfortably on a height-adjustable chair and was asked to wear the eye-tracker goggles. The experimenter first briefed the participant regarding the experiment and asked the participant to follow a 15 seconds calibration procedure for the gaze measurement. The task began with the participant resting for 3

Response to Question	≥ 70% of time looked at Face_ROI	System Response [Label]
Right	Yes	Your classmate really enjoyed having you in the audience. You have paid attention to her and made her feel comfortable. Keep it up! [S1]
Right	No	Your classmate did not know if you were interested in the presentation. If you pay more attention to her, she will feel more comfortable. [S2]
Wrong	Yes	Your classmate felt comfortable in having you in the audience. However, you may try to pay some more attention to her as she makes the presentation so that you can correctly understand what she is telling. [S3]
Wrong	No	Your classmate would have felt more comfortable if you had paid more attention to her. Also, you may try to pay some more attention to her as she makes the presentation so that you can correctly understand what she is telling. [S4]

Table 1: Rationale behind Attention-based Real-time Motivational Feedback.

minutes to acclimate himself with the experimental set-up. Participants viewed the initial instruction screen followed by an interaction with the avatar narrating a personal story for classmates. Each storytelling trial was approximately 3 minutes long. The participants were asked to imagine that the avatars were classmates at school giving presentations on several different topics. They were informed that after the presentations they would take a quiz on a basic fact about the content of the presentation. They were also asked to try and make their classmates as comfortable as they could while listening to the presentation. However, it was not explicitly stated that in a presentation a speaker feels good when the audience pay attention to the speaker (by looking towards the speaker). The idea here was to give indirect feedback to the participants about their viewing patterns and thereby study how that affects the participants as the task proceeded. The experiment began with the avatar narrating a personal story in each trial. After each trial, the participant was asked a story-related question. The participant responded with a keypad. Each participant was compensated in the form of gift cards for completing a session.

In our study, the participant served as audience while the avatars narrated their personal stories. Then the participant responded to question asked by the system. After the participant's reply, an audio-visual feedback, which was computed based on the real-time gaze data to determine the actual time the participant spent looking at the face of the avatar during the presentation, was provided to the participant. The feedback had two parts. First, it informed the participant whether their answer to the story-related question was correct. Second, based on how they responded to the question and how much attention they paid to the presenter (i.e., avatar), the system encouraged them to either pay more or keep the same attention towards the presentation. Table 1 shows the system's responses for providing feedback to the participant.

Results

Feasibility of VR dynamic eye-tracking response technology The first goal of the present study was the development of a system that allowed for integration of dynamic eye-tracking with VR-based interaction, such that the VR system pin-points quantitatively, where and how long a child is looking using metrics such as fixation duration. Results of the current study were promising with regard to participant experience, quantitative measurement of gaze pattern, and real-time calculation of specific gaze measurements that could guide specific adaptive responses and intelligent, automatic decision-making.

With regard to participant experience, all six participants adequately tolerated the session and we were successful in obtaining continuous real-time measurements of gaze throughout every interval of the session for each participant. Further, anecdotally five of the participants asked regarding possibilities to participate in future projects.

Regarding system capabilities, through continuous data acquisition of gaze coordinates within the viewing stimulus (i.e., x and y coordinates) (Figure 2) we were able to acquire an average assessment of 141.33 seconds of data across the approximately 180 seconds interval for each trial. This represents approximately 78.52% of the total trial time and suggests that the participant spent a major portion of their time looking towards the visual stimuli. The other smaller percentage of time is accounted for by participants looking outside of the presented visual stimuli and/or not fixating on the visual stimuli. As such, incorporation of fixation duration metric for off-target viewing would account for nearly 100% of the trial time. In addition, to defining specific ROIs, the system was also capable of generating scan paths for the entirety of the trials in the background, when the participants' gaze could be coordinated (e.g., Figure 3). This was done as individuals with ASD have been shown to exhibit atypical scan paths during social communication tasks [29-30]. For the purposes of the current study, we defined three ROIs in order to develop metrics to utilize this continuous data acquisition, but the capacity to acquire such a continuous measurement of scan path would afford for numerous alternative constructions of ROIs as well as switches to or from specific stimuli within the field over time.

While numerous other researchers have demonstrated the ability to effectively implement eye-tracking paradigms, in the current work we were ultimately attempting to demonstrate the feasibility of utilizing such a paradigm to automatically structure and adapt interactions in real-time. We captured 78.52% of the dynamic gaze data of the participants and analyzed the scan paths between their gaze fixation points distributed over the different ROIs of the presented visual stimuli. Although we chose to accumulate this data via a summary score tied to hypothetically meaningful aspects of a specific virtual social task with the system at the end of 3 minutes of data collection, a thorough assessment of system capability suggests such summary scores could be generated every 33 milliseconds or

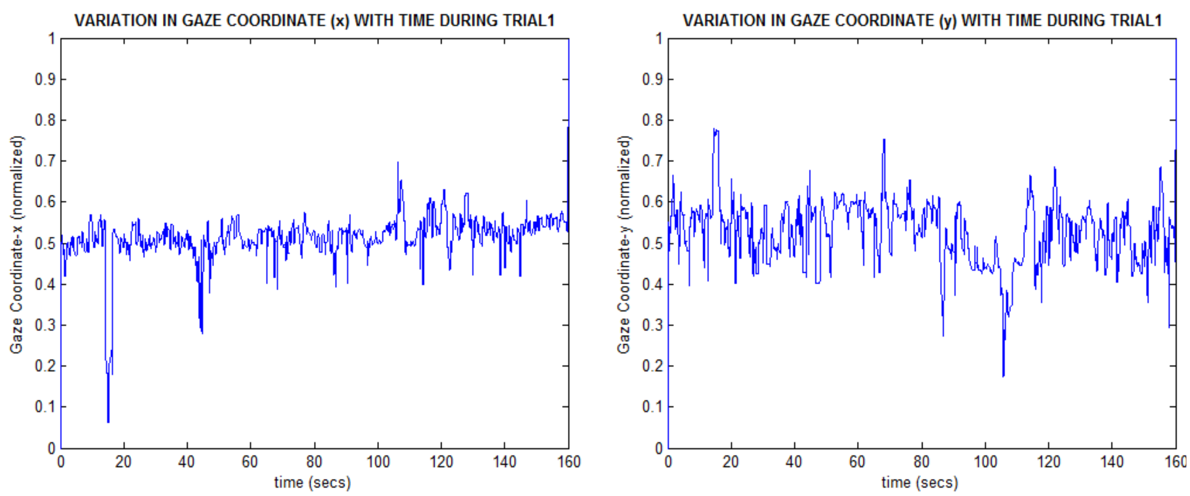

Figure 2: Real-time variation in Gaze Coordinates for participant in one trial (Trial1).

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any specific iteration thereof (i.e., an estimated 5454 possible calculations during our total 3 minutes interval or 4283 calculations across the average 141.33 seconds of data within this protocol). While such immense numbers of calculations present challenges for creating appropriate decision-making capacity at each interval, it does suggest that near real-time adaptation based on eye-gaze data is possible.

Impact of adaptive technology on behavioral viewing patterns

While it is important to restate that the current study was not an intervention trial, but a usability study and pilot investigation of the developed technology, we did examine the impact of the adaptive technology on behavioral viewing patterns. Specifically we examined changes in terms of both Fixation Duration and Object-to-Face Ratio in the course of the five trials of the experiment.

We first examined the impact of adaptive feedback on the total fixation duration while the participants (ASD1-ASD6) viewed the face region of interest. There was substantial variation across subjects (Figure 4) both in terms of the amount of time spent looking at the face during the first trial (range = 41.31 seconds to 146.37 seconds) and at the end of the four adaptive response trials (range = 77.78 seconds to 179.49 seconds). All participants demonstrated improvements in terms of time spent looking at the face region of interest from initial trial (M = 101.49 seconds, SD = 43.76 seconds) to final trial (M = 142.89 seconds, SD = 39.38 seconds), with a dependent samples t-test indicating that this was a statistically significant change for the groups ($t = 8.068$, $p < 0.001$).

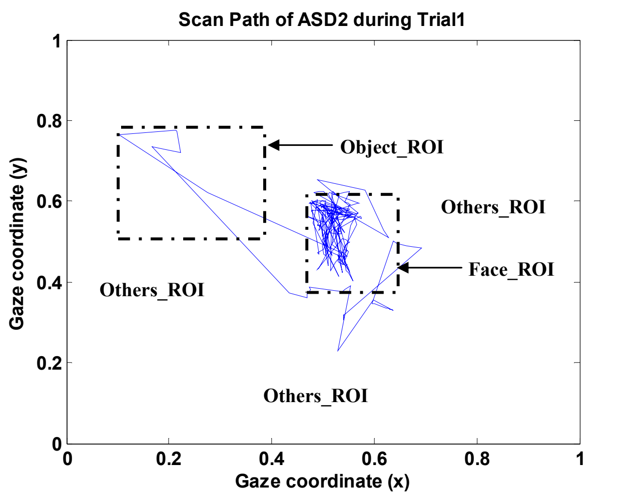

Figure 3: Scan Path of participant during Trial1.

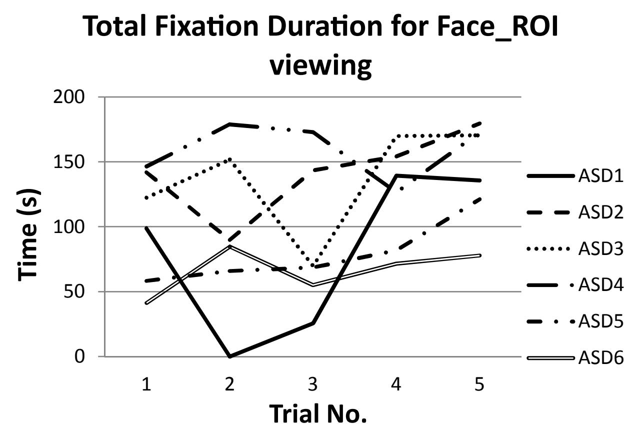

Figure 4: Variation in Total Fixation Duration (FDTOTAL) for Face_ROI viewing.

We then examined the impact of adaptive feedback on the ratio of time spent looking toward the context-relevant object versus the face region (i.e., OFR) within the presented visual stimulus. There was substantial variation regarding initial OFR (Figure 5) for participants (M = 0.1649, SD = 0.12) with all participants demonstrating a decline in terms of spending little to no time looking at the object during the presentation at final trial (M = 0.0068, SD = 0.01). Again a dependent samples t-test suggests that there was a statistically significant change for the groups ($t = 3.172$, $p < 0.05$). Interestingly, 3 of the participants shifted toward spending no measurable time looking at the object during the final trial.

Discussion

Prior research has demonstrated that children with ASD commonly exhibit atypical viewing patterns, such as greater fixation towards non-social objects than human faces during social interaction [15]. Explanations of such aytpical viewing patterns include not only description of potential underlying neurobiological differences, but also descriptions of differences in regulating social attention and differences in social motivation [31-32]. Regardless of definitive understanding of origins or sustaining developmental and biological mechanisms, differences in viewing patterns are thought to be on a basic level. These result in reduced time attending to faces, language, and other social stimuli, and as a direct consequence on a complex level contribute to decreased expertise in numerous social skill-related areas, with such difference leading to a cascade of negative consequences for development in children with ASD. Thus, developing systems capable of carrying out investigation of the viewing patterns on basic levels has the potential for addressing complex down-stream impairments associated with ASD. In this work, we set out to a) develop a new technology-based system that could measure gaze information and provide dynamic feedback during social interaction tasks presented in a VR environment and to b) assess the technological capacity of such a system to adaptively respond to the behavioral viewing patterns and its implications on a small sample of children with ASD. In this investigation, we were able to develop a prototyped model of VR-based interaction system for children with ASD with the ability to process gaze information in real-time and communicate this to the VR environment to provide feedback to the participants based on their instantaneous interaction with the virtual social world. While our feedback mechanism was limited to providing systematic information about performance and gaze behavior at the end

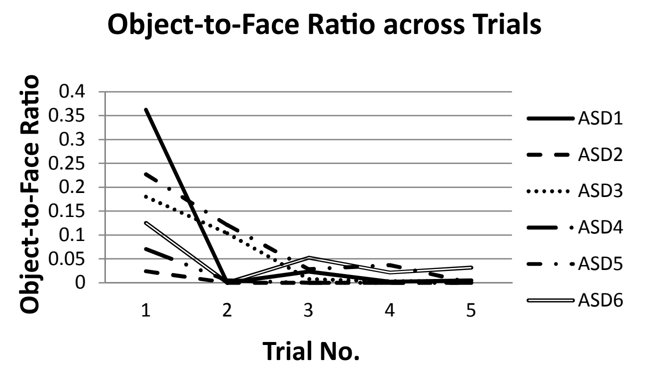

Figure 5: Variation in Object-to-Face Ratio (OFR) across trials.

of a several minute interval, we actually realized capability for calculating viewing indices in real-time (i.e., every 33 milliseconds). Thus, while our technology paused and presented feedback to participants within fairly discrete training trials, ultimately the developed technology is capable of providing feedback on one's behavioral viewing in an on-line, continuous manner. Such capability suggests great potential for flexible intervention paradigms. For example, one's behavioral viewing could be continuously monitored and feedback could be conveyed to the participant when they are not paying proper attention. In this manner, the developed technology reported here could be integrated into a more complex and sophisticated social interaction task to achieve targeted goals if paired with appropriate reinforcement paradigms.

In terms of investigating the implications of this technology while performing usability study with adolescents with ASD, results are promising, yet several potent methodological considerations limit interpretation of our findings. The VR-based social task designed for this study was employed as a first step in evaluation of the benefits of such a technological system for children with ASD. Quite simply this technology provided children with specific feedback based on quantitative measurement of their performance and viewing pattern. In this manner, children were simply receiving feedback about whether they were socially communicating in a manner which was above a specific threshold or answering questions correctly and when they were not, they were told how they might improve their social interaction. In this way our VR-based social task was ultimately providing an extrinsic measurement that may be linked with enhanced self-monitoring and performance rather than a sophisticated reinforcement paradigm scaffolding complex layers of skills. Even with this limit, all children were able to demonstrate improvements in terms of a) looking at faces of virtual peers (avatars) for a longer duration as well as b) looking at nonsocial object for less time as the trials proceeded, while interacting with our system capable of providing feedback. These findings are seen as indicative of potential for change within more sophisticated systems that may also include measurements of atypical fixed gaze and atypical switching as opposed to the simple threshold measurement presented here.

Although the present study demonstrated the technological capacity for real-time gaze-based technology for children with ASD, the findings of this study are preliminary and limited in nature. While demonstrating proof of concept of the technology and significant trends of 'improved' behavioral viewing in a VR-based social task, questions about the practicality, efficacy, and ultimate benefit of the use of this and other technological tools for demonstrating clinically significant improvements in terms of ASD impairment remain. The study itself focused on a limited number of high-functioning participants and while some initial improvements were seen within the system, there was no evidence that this technology realized change for participants outside of the limited environment of the experiment itself or over time. Also, participants in this study possessed cognitive profiles of relatively intact skills, suggesting that questions about how such a technology might apply to a more representational sample of children across the spectrum are relevant.

Despite these potent limits, the results of the current study are promising in terms of demonstrating a new modality which can serve as an assistive tool for ASD intervention. We believe that there is potential for emerging technology to play a significant role in providing more accessible and effective intensive individualized intervention in the future. There are numerous reasons why incorporating technology, specifically eye-tracking and VR systems, into intervention practices may be particularly relevant for children and adolescents with ASD. Specifically, computer and VR intervention methodologies potentially have the ability to address the substantial difficulties with generalization of learned skills to the real-world by introducing not only more control over teaching basic elements of complex skills, but also the ability to systematically employ and reinforce these skills within many different, controllable, realistic interaction environments [33]. Traditional methods of social and adaptive skill intervention often are not able to control environments or repeat exposure to naturalistic environments with an intensity that may lead to more substantial change [34]; however, the virtual world can be designed to break down, repeat, add, and subtract aspects of the environment in any manner necessary to achieve a task goal.

Employing appropriately individualized paradigms within technological systems can endow intervention tools with the ability to automatically detect, appropriately respond, and adapt reinforcement based on individual performance and attentive needs of the children with ASD. Historically, one of the greatest barriers to progress in development and implementation of interventions for individuals with ASD across the lifespan is the heterogeneity of the spectrum itself. Although core social communication features and stereotyped behaviors characterize individuals with ASD, these features and behaviors are present at varying degrees across the spectrum. A clear need exists to advance understanding of the numerous phenotypic variations inherent to ASD. However, present intervention science is not capable of specifying appropriate interventions for each individual with ASD in a broadly applied data-driven fashion. In this respect, a sophisticated integrated technology with a behavioral profiling system capable of adapting controlled environments and reinforcing skills in core domains gradually but automatically could prove an effective tool for developing tailored interventions for individuals with ASD. In a sense, deploying such technological tools could make targeted and personalized intervention a reality for these individuals and could be incorporated into complex intervention paradigms aimed at improving functioning and quality of life for older children, adolescents, and adults with ASD. Although sophisticated, individualized VR systems are not at present widely available in many intervention settings, the barriers to optimal, intensive behavioral and educational intervention are so potent and the costs associated with suboptimal intervention so great, that the development of such tools may be actually more practical, cost-effective, and beneficial than currently available intervention approaches/modalities.

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