The Effects of Social Presence on Gaze, Movement, Arousal and Blink Rate in Autism: A Cooperative Virtual Reality Game-Based Approach

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***Abstract*—Difficulty in social interaction is a key factor in the diagnostic criteria for autism. Although not fully understood, fluid human social interaction demands a complex exchange of verbal and non-verbal signals, which is disrupted in autistic individuals. Differences in gaze behavior, gross motor movement, and physiological responses related to arousal and attention have been observed repeatedly in autistic individuals, potentially impacting social interaction. Our prior work [1] uses a fully immersive virtual reality video game custom-designed to examine the role of social presence through solo and cooperative versions of the game. We predicted that the inclusion of a virtual presence would impact the temporal execution of gaze behaviors and gross motor movements, as well as modulate physiological arousal and blink rate in autistic individuals differently than non-autistic controls. We found that the cooperative condition produced a larger number of differences in gaze behaviors and gross motor movements for autistic individuals. Additionally, arousal and blink rate displayed differences during the cooperative condition. These findings demonstrate the specific effects of a virtual social presence on fundamental behaviors that comprise social interaction and can be measured and eventually manipulated in virtual reality.**

I. Introduction

Human sensorimotor systems are exquisitely responsive to environmental dynamics with visual input being primary in directing orienting behavior. This is, in part, what makes social interactions so fast and fluid. In this study, we evaluate how the use of gaze, gross motor movement, and physiological responses for arousal and blink rate change depending on two different social contexts. Gaze behavior is the physical expression of visual attention and is used for gathering information about an environment [2]. To operate successfully in an environment, humans use past experiences to produce a unique pattern of gaze behavior that directs attention to the most relevant aspects of the scene [3], [4]. Similarly, gross motor movements are generated based on the collected sensory information and prior experiences [5]. When these gaze and gross motor actions are part of a social interaction, the feedback received from others is processed and used to select particular actions to perform during similar future interactions.

The feedback from one's own actions as part of social interactions also produces changes in the autonomic nervous system, which modulates physiological arousal state [6]–[8]. Aspects of both task engagement and physiological arousal have been related to the state of flow [9], [10]. We can say that aspects of task engagement can be used to describe the experience of one who is in a flow state, aligning with one of the nine descriptors of flow behaviors [11], whereas indices of physiological arousal reflect these states of behavior. We can readily index some aspects of arousal via pupil diameter [12]. Similarly, task engagement and the mental load it brings have been related to blink rate, with increased mental load related to decreased blinking [13]–[15]. This information flow involving sensory context, motor actions and feedback signals is part of the complex system humans use in planning movements, which are especially dynamic and sensitive for social interaction. Like other differences in the human condition, we also differ in the degree of social skill we bring to interactions.

Autistic individuals are, by definition, a group of people who experience challenges in social interaction. Autism is defined by the Diagnostic and Statistical Manual of Mental Disorders, Fifth Edition, Text Revision (DSM-5-TR) as a neurodevelopmental condition characterized by impairments in social communication and repetitive behaviors or interests [16]. The selection of appropriate behaviors for social interaction is based on past experience within a particular context and can differ quite substantially for autistic individuals [17]. Different early orienting and visual attention behaviors have been observed in infants later diagnosed as autistic [18] with differences in observed gaze behavior persisting into adulthood [19]–[21]. Specific gaze-based differences in autism include irregularities in eye contact, difficulty in visually tracking objects, and irregular fixation time to specific types of stimuli. When asked to look at social stimuli like a human face, autistics show different patterns of gaze from non-autistics, which manifest as less time focusing on the eye and more time focus-

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ing on the mouth. The causes of these gaze differences are not well understood, but it is apparent that they are affecting the fluidity and timing of social interaction to some degree [22]. Similar to gaze, prior studies have demonstrated substantial differences in autistic gross motor movement [23]–[25]. It is possible that temporal differences in movement and gaze are contributing to the issues with autistic social interaction. Multiple studies in autistic individuals also observed temporal differences in motor planning of a wide range of movements, including gestural, fine, and gross motor movement [26]–[28]. Data from these and other studies reveal challenges in manual dexterity in autistic individuals on tasks like the grooved pegboard [29], [30] extend into other motor tasks that demand precise spatiotemporal accuracy and synchronous co-operative movement [31]–[33]. For example, movement tasks that require precise visuospatial and/or temporal integration demands, such as ball catching, are the most impacted [34] when compared to non-autistic individuals. Issues with these kinds of tasks that require coordination of various kinds of gross motor movement, like the head and hands in parallel with gaze, illustrate a larger picture of autism that involves multiple different domains. Gaze and movement are the two primary methods humans use to navigate and interact with their environment, so differences in these domains can understandably create difficulty in integrating dynamic sensory information and producing sophisticated movements. While vastly more complex than catching a ball, social interaction requires the precise use of gaze and gross motor movement in order to interact effectively with others.

Movement time for gross motor movements has been used to assess an individual's integrated perceptual and motor responses to specific task demands [35]. In order to reliably measure the total duration of movement sequences that incorporate gaze and gross motor movement, we use head-mounted virtual reality (VR), which offers the user a fully immersive 3D experience as well as technology to detect user movement. Using a dynamic VR video game, we are able to reliably measure natural movement sequences involving gaze and upper limb movements. In previous research, the measurement of movement sequences has faced some criticism due to its potential lack of ecological validity [36] involving discussions about the size of the screen not replicating a real-life performance environment. These critiques cast legitimate doubt on the transferable nature of results recorded in a laboratory setting. Using VR, we can mitigate this potential lack of ecological validity by giving the participant a fully immersive 3D experience while retaining excellent environmental control.

As stated above, these autistic differences in gaze and, to a slightly lesser extent, movement have been reliably studied and validated over the past decade. To better understand how a sophisticated behavior like social interaction is affecting autistic individuals, this study also evaluates changes in physiological arousal. Arousal is an autonomic process connected to the body's autonomic nervous system. The sympathetic nervous system responds to situations that are perceived to be stressful or dangerous and helps direct attention and control movement responses toward or away from stimuli as is appropriate for the situation. This release has complex and potentially opposing effects on both the sympathetic and parasympathetic nervous systems. The primary and most common effect of a stress challenge is through the activation of the sympathetic pathway resulting in the dilation of the pupil. Changes in pupil diameter have been shown to be a reliable method of measuring arousal in humans [12]. Irregular arousal responses have been found in autistic individuals for a variety of different situations [37]. While it is unclear at this time why arousal irregular in autistic individuals, some research indicates that arousal measured via pupil diameter differs between autistic and non-autistic individuals when observing social stimuli [38]. In this study, we observe arousal responses in social and non-social contexts in relation to specific movements facilitated by the game mechanics.

Presence, or the feeling that you are actually in a location, is important to establish validation and generalizability of behaviors executed in the virtual environment (VE) onto real-world behavior [39], [40]. To increase the perception of presence within the VE of our game, participants were given virtual hands and a head, which were visible to the player and their partner in the virtual environment. These embodied graphical elements have been linked to an increased sense of presence in other studies [41]. The control of virtual avatar body parts in the context of a video game is associated with higher levels of engagement, focused attention, a sense of presence, and flow [42]. By converting the task into a game, and by keeping players engaged within the task, we expect to generate more consistent behavioral responses. This VR game seeks to examine foundational physical behaviors and physiological responses that comprise social interactions through an immersive and engaging task.

In summary, with the VR game described in this report, we are able to characterize how the inclusion of a virtual social presence affects autistic and non-autistic gaze, movement, and physiological responses. By modifying the nature of gameplay to include solo and cooperative conditions, we can observe changes in these measures across social and non-social contexts. We hypothesize that autistic players would perform gaze and gross motor actions more slowly than non-autistic players, and that a social presence in the cooperative condition would magnify this effect. Additionally, we hypothesized that autistic players would have a larger arousal response to executing gross motor in-game tasks than non-autistic players in the cooperative condition. We might similarly expect greater engagement for both groups in the cooperative task as observed through blink rate with perhaps this engagement carrying more mental load for autistic players. It is our aim to establish a paradigm for dynamically evaluating behavioral and physiological responses to social situations, so that we might better appreciate the variation in human processing social interaction.

II. Methods

A. Participants

We recruited participant volunteers from a convenience sample during the 2022 Neurodiverse Summer Internship program focused on game design and development hosted at UC San Diego and Northeastern University. Autistic participants (male = 9, female = 2; $n = 11$) had a community diagnosis of autism (i.e., a formal diagnosis from a medical professional in the community), all of whom participated in the summer internship. Autistic participants were participants in an internship program designed to support autistic young adults in game design and development. All participants used spoken language as their primary means of communication and had the capacity to work collaboratively in groups on a highly technical and time-intensive project. Due to the sensitivity of this group's current working condition at the time of data collection, we did not confirm an autism diagnosis with clinical tools. As such, we did not measure autism symptom severity in either group and, therefore, do not examine the relationship between symptom severity and different movement and physiological responses. We also recruited 16 non-autistic participants from the university communities ($n = 10$ from UC San Diego; $n = 6$ from Northeastern; male $= 8$, female $= 8$). The mean age of the sample was 24.3 years, ranging from 18 to 27. This study was approved by Institutional Review Boards at both UC San Diego and Northeastern University.

B. Overview

We created a custom VR pattern-completion game in Unity3D that can be played independently or as a cooperative dyad via a networked internet connection. Across both cooperative and solo conditions, gaze, gross motor behavior, arousal, and blink rate were evaluated using the Vive Pro Eye Head Mounted Display (HMD), handheld motion-tracking controller, and integrated eye-tracking hardware. Participant's gaze behavior was interpreted based on measures of gaze duration and gaze transfer rate between areas of interest (AOI). Gross motor movement was evaluated as the total movement time for specific in-game events requiring upper limb coordination. Arousal measurement was event-aligned and evaluated based on the timing of specific in-game gross motor movements. Blinks were monitored throughout the game and evaluated as blinks per minute.

C. Procedure

Following informed consent, participants were given a Vive Pro Eye VR headset to wear, which was adjusted with the help of an experimenter to be comfortable and secure on the participant's head. Participants were instructed to remove the headset immediately if they felt sick. However, we experienced no issues with motion sickness during the study. After securing the HMD, experimenters calibrated the Vive Pro Eye's built-in eye tracker using a 6-point calibration program. As the participant was undergoing this setup, an experimenter prepared a second VR HMD and computer station to use for the cooperative condition. Using the Photon Engine in Unity, this game linked the two computer/HMD stations, enabling multiple people to enter the same virtual environment.

Following the setup and calibration, participants completed the first tutorial, which explains the rules and allows them to practice the game mechanics. During this tutorial, which lasted 2–3 minutes on average, experimenters explained the overall objectives of the game, as well as instructions on how to use the VR equipment. Once the participants could perform the game without assistance and gave verbal confirmation that they understood the objectives, the experimenter stopped the tutorial, and the solo trials began. Following the successful completion of two solo condition trials, participants began a second tutorial, again lasting 2–3 minutes, introducing the experimenter-controlled virtual partner. During the tutorial, the 2 players practiced for a short time until the participant could play independently and gave verbal confirmation that they understood what to do. Following this tutorial, the final two cooperative condition trials were conducted. Each of the four trials lasted approximately 5 minutes but varied based on each participant's speed in completing each trial. After completing all 4 trials, participants removed the headset and were debriefed on the design and impact of their participation. We observed no instances of participant confusion in the game, and all participants were able to finish the entire protocol without pause. To maintain consistency, the same individual experimenter was used as a partner for each participant. The study lasted approximately 30 minutes, and participants received $10 compensation.

D. Game-Based Task

We developed a custom, fully immersive game-based task for this experiment using Unity version 2019.3.13. The game is a 3D pattern completion game where the primary objective is to recreate a 5×5 pattern of colored cubes as fast as possible. This game was designed to facilitate a variety of different types of gaze and movement behaviors. The environment was set up with three AOI, each of which required the player to use different kinds of movement and gaze. The pattern was presented to the player on a nearby structure in the virtual environment (see Figure 1) termed the View Wall. During gameplay, players moved their handheld VR controller to direct a virtual laser (ray-cast) extending from their right hand to interact with objects around them. Using the trigger button on the controller, the player could grab cubes from another virtual structure termed the Play Wall. The Play Wall spawned new cubes at the top of the Wall and contained them as they fell downward toward the bottom of the Play Wall. The cubes fell at a constant speed of 1 (m/s) when converted to real space for 8 seconds before the cubes hit the bottom of the Play Wall, and they despawned. The player could grab these descending cubes at any point from their moment of spawn until they disappeared at the bottom and use them to build the View Wall pattern. To do this, the player had to turn to their right and place the cube they grabbed into the last virtual structure, the Build Wall. At the start of the game, the Build Wall starts as an empty 5×5 structure in the virtual environment, topped with five green Drop Zones heading each column. Placing a cube into one of the five Drop Zones triggered the cube to descend to the lowest non-occupied row in the column, much like the popular tabletop game Connect Four. If a player made a mistake and placed a cube on the incorrect Drop Zone, the player had the ability to select the cubes on the Build Wall that they wished to remove, and the cubes would be deleted. The player was unable to submit their pattern and end the game unless the created Build Wall matched the pattern displayed on the View Wall.

To better understand how different kinds of dynamic stimuli affect the use of gaze and movement during social interaction, the three Walls were designed to either contain or withhold various degrees of dynamic stimuli. The Play Wall contained moving objects that the players had to find and grab, the Build Wall contained stationary objects that the players had to place objects into, and the view wall necessitated no gross motor movement, and only gaze was required. The different stimuli found on each Wall provoked the players to use different skills when interacting with them. Although not a proper social interaction, this amount of complexity is much more similar to a realistic scenario where multiple different things can be happening all around you. We observed differences in interactions with each wall between autistic and non-autistic individuals. We interpret these differences in light of the kind of stimuli each wall contains and how that may contribute to differences in social interaction.

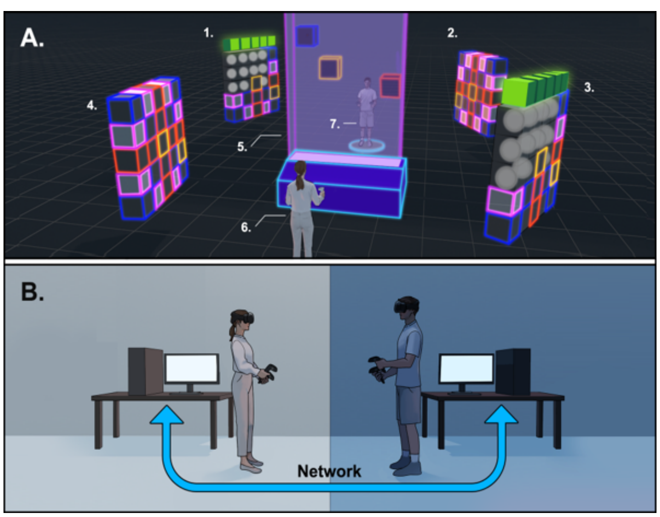

Fig. 1. **A.** Virtual Environment: 1) Player-1 Build Wall, 2) Player-1 View Wall, 3) Player-2 Build Wall, 4) Player-2 View Wall, 5) Play Wall, 6) Player-2, 7) Player-2. **B.** Real World Environment

All patterns in the game were composed of four types of colored blocks: red, blue, white, and gold. To control for any changes in pattern difficulty, the same four patterns were used for each of the solo and cooperative trials. In the solo condition, all four of these cubes could be grabbed by the participant/player who was responsible for individually completing the pattern. However, in the cooperative condition, the colors of the cubes indicated who and how the two players could grab cubes. While both players could still grab the white cubes, the red and blue cubes could only be accessed by one of the two players. Grabbing a gold cube required both players to be holding the same gold cube on the Play Wall. Once both players grabbed the same gold cube, each would be given half of the cube (right half for one player, left half for the other), which they could put into the Build Wall. If a right and left half were put into the same spot on the Build Wall, the two halves would combine into a whole gold cube. After a cube was successfully placed into the mutual Build Wall, either player was able to take it off and delete it regardless of color. These mechanics were designed to increase the cooperative nature of the task while not changing any of the specific measures between conditions. The participants were instructed not to communicate verbally during the game, so players made decisions and coordinated their actions based on the visual state of the environment. Since both players actively contributed to building the same pattern in the cooperative condition, this division of labor enhanced cooperation but also reduced the time needed to complete the task since the size of the pattern stayed the same.

E. Measures

Gaze: Using the Tobii Eye-Tracking VR SDK, gaze data was collected at a sample rate of 90Hz via a custom script that monitored the location of the directed gaze inside the virtual environment. Gaze behavior was first evaluated as a measure of gaze duration, which is the amount of time that a participant spends fixating on a specific AOI (Play Wall, Build Wall, and View Wall) before transferring their attention to another location. The second measure of gaze behavior we observed was the gaze transfer time between AOIs. Each of the three AOIs in the game required participants to shift their attention back and forth between them depending upon their unique strategies for completing the pattern given on that trial. Gaze transfer time was defined as the amount of time starting when the participant's gaze left one AOI and arrived at another.

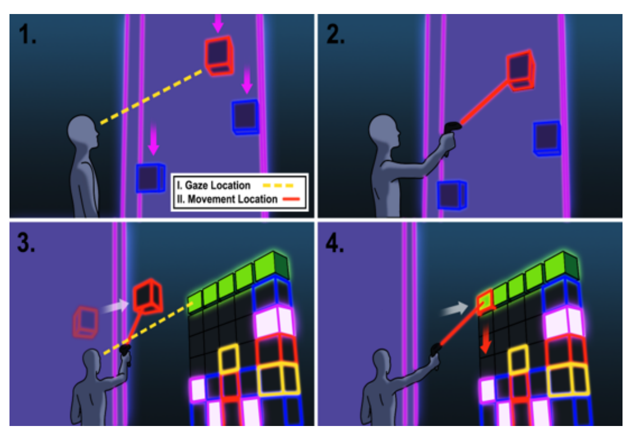

Fig. 2. **Cube Grab Movement:** 1) The player visually finds a cube on the Play Wall. 2) The player moves their arm, holding the Vive Controller to grasp the cube. **Cube Placement Movement:** 3) The player visually finds the Drop Zone on the Build Wall. 4) The Player moves to place the cube onto the Drop Zone in the Build Wall.

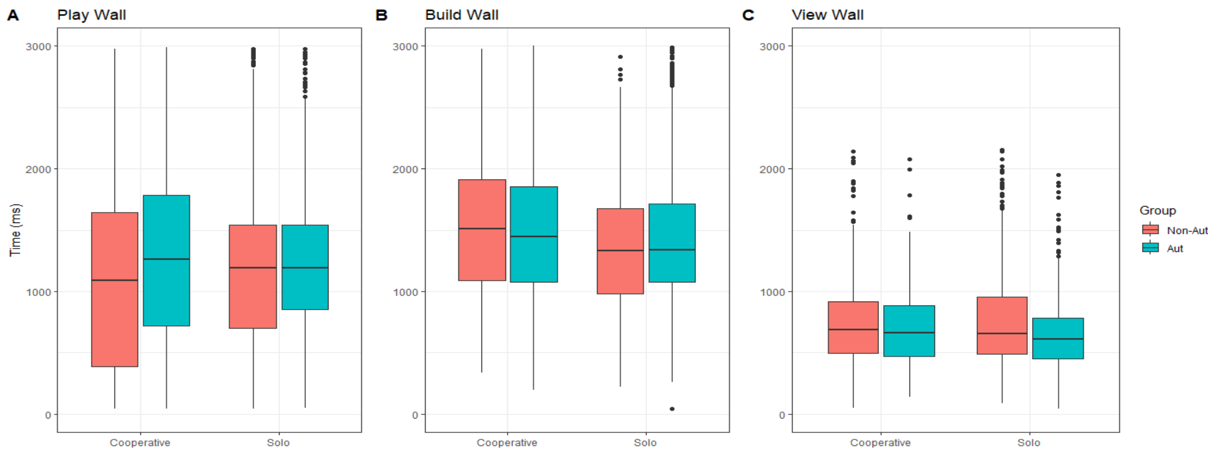

Fig. 3. Gaze duration times for A) Play Wall, B) Build Wall, and C) View Wall. The two groups are Non-autistic (red) and autistic (blue). Each plot shows the upper and lower quartile of the group's mean fixation duration. The median of each group's data is indicated by the center line of each box.

Movement Time: This game required all participants to produce three specific movement sequences that can be compared across both solo and cooperative conditions. Two of which, grabbing and placing cubes, are shown in the conference paper [1] of this study. For this paper we have included an additional third measure that evaluates the transfer of cubes from the Play Wall to the Build Wall.

- Cube Grabbing: As shown in Figure 2 (sections 1-2), this movement began when the participant visually found a cube descending the Play Wall and completed when the participant then grabbed the cube with the Vive Controller.
- Cube Placement: As shown in Figure 2 (sections 3-4), the participant visually found a Drop Zone on the Build Wall, started the sequence, and then placed the cube onto the Drop Zone to complete it.
- Grabbing to Placement: As shown in Figure 2 (sections 2-4), this movement started when the participant grabbed a cube on the Play Wall and ended when they have shifted their attention to the Build wall and placed it into a Drop Zone.

Arousal: Pupil diameter (mm) was recorded to index the participant's arousal level. An increase (decrease) in pupil diameter was interpreted as an increase (decrease) in arousal. We measured pupil size using eye-tracking cameras in the HTC Vive Pro Eye. Pupil size is recorded from the eye cameras along with each estimate of gaze direction. The data were extracted and analyzed using a custom Unity script and the Tobii Eye-Tracking VR SDK. Our analysis of arousal [1] considered epochs of 1-second intervals around movement events for grab or place, see Figure 8. An additional measure separating those movements has been added using the same techniques in Figure 9. Since pupil size has a slowly varying natural baseline, we used average pupil size for 1 second before the hand event as an estimate of the ongoing baseline pupil size and subtracted it from each epoch. Then, we collected each trial and binned the pupil diameter in 100 ms intervals to create baseline corrected averages of the percent change in pupil diameter for each participant. We used a measure of percent change compared with baseline to account for the natural variability in pupil size across participants. Variability was represented by an across participant standard error. In this paper, we also separated the hand events to evaluate grabbing and placing separately.

Comparison	Condition	Group	Mean (ms)	t	df	p
Gaze Duration: Play Wall	Solo	Aut	1323.81	0.367	2060	0.713
		Non-Aut	1309.9			
	Cooperative	Aut	1634.52	3.448	914.37	<0.0001*
		Non-Aut	1309.9			
Gaze Duration: Build Wall	Solo	Aut	1359.26	-2.29	1430	0.02*
		Non-Aut	1439.2			
	Cooperative	Aut	1668.2	3.054	615.79	0.002*
		Non-Aut	1491.23			
Gaze Duration: View Wall	Solo	Aut	661.5	-3.941	658.72	<0.0001*
		Non-Aut	762.71			
	Cooperative	Aut	712.82	-0.88	384.33	0.379
		Non-Aut	738.91			
Gaze Transfer: Play -Build	Solo	Aut	265.72	-1.418	1518.1	0.152
		Non-Aut	280.56			
	Cooperative	Aut	297.58	3.456	426.91	0.006*
		Non-Aut	224.23			
Gaze Transfer: Build -Play	Solo	Aut	306.89	3.048	1065.8	0.002*
		Non-Aut	267.24			
	Cooperative	Aut	228.3	-0.06	582.38	0.952
		Non-Aut	229.11			
Gaze Transfer: Play - View	Solo	Aut	57.14	-0.474	297.62	0.6355
		Non-Aut	60.29			
	Cooperative	Aut	228.3	-0.06	582.38	0.952
		Non-Aut	229.11			
Gaze Transfer: View - Play	Solo	Aut	47.01	0.89	401.22	0.3738
		Non-Aut	44			
	Cooperative	Aut	49.03	1.618	256.59	0.106
		Non-Aut	42.66			

Fig. 4. Unequal variance t-test comparing gaze metrics between groups across conditions, including test statistics, degrees of freedom, p-values

Blink Rate: Blink rate is associated with task engagement and mental load [13], [14], [43], with fewer blinks indicating greater engagement and possibly increased mental load. To measure this, we evaluated blinks at a rate of blinks per minute during each of the game's trials and conditions. Using the Vive Pro Eye integrated eye-tracker, we recorded blinks by evaluating lapses in gaze recording and filtering the resulting data. Lapses in gaze data recording within a range of 0.07 to 0.3 seconds were registered as a blink [44].

Statistical Analyses:

For each measure of gaze or gross motor behavior, we conducted two unequal variance t-tests per condition to determine any within-group differences between the autistic and non-autistic groups. Unequal variance t-tests were chosen due to the unequal number of samples gathered for each participant during each trial. The mechanics of the game permitted each participant to use gaze and movement slightly differently in order to accomplish the goal of the game. Each individual sample was classified based on the participant's group and the condition under which it was performed before analysis. To evaluate arousal and blink rate, a two-way ANOVA was performed to determine any differences or interactions between groups and conditions. This alternative analysis was chosen because these measures were consistent between each participant across both conditions.

III. Results

The aim of the current study was to examine potential differences between autistic and non-autistic groups while completing solo and cooperative versions of a VR pattern completion game. The null hypothesis states that there are no differences between groups, and any significance found ($p < 0.05$) via our analyses suggests a difference and acceptance of an alternative hypothesis. A broad evaluation of the various measures from this experiment will help illuminate the foundational contributions to the differences observed in autistic social interactions.

A. Gaze Behavior

Shown in Figure 4, a table of comparisons between groups for each measure of gaze behavior is shown using an unequal variance t-test. For gaze duration on AOI within the game, the autistic group spent significantly longer on average attending to the Play Wall ($p < 0.0001$) and the Build Wall ($p = 0.002$) in the cooperative condition. The non-autistic group spent significantly longer looking at the Build ($p = 0.02$) and View Walls ($p < 0.0001$) on average during the solo condition. No statistical difference was shown for gaze duration on the Play Wall during the solo condition and the View Wall during the Cooperative condition. In Figure 3, the median and variation of these data are displayed. Some of this data is shown in the conference paper [1] for this study; however, in this report, we divide each individual sample of the measure by group, while in the former analysis, we compared the means of each participant's generated samples. This change was made to give additional statistical power and accuracy to the analysis.

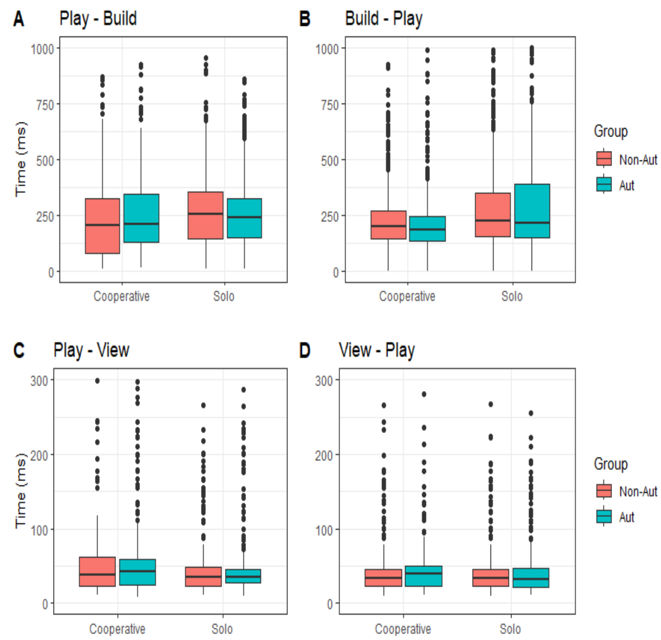

Fig. 5. Gaze transfer times between the three AOIs. A) Play Wall to Build Wall, B) Build Wall to Play Wall, C) Play Wall to View Wall, B) View Wall to Play Wall. Non-autistic (red) and autistic (blue) participant data shown.

We also characterized gaze transfer time as the time to shift between AOIs (see Figure 5). The table in Figure 4 shows the group comparisons for each gaze transfer time between AOIs for each condition. The autistic group took significantly longer than the non-autistic group to transfer their gaze between the Play Wall and Build Wall ($p < 0.0001$) in the cooperative condition. The non-autistic group took significantly longer to transfer their gaze between the Build Wall and Play Wall ($p = 0.002$) during the solo condition. There was no significant difference between groups found in gaze transfer time between the Play to Build Walls for the solo condition and the Build to Play Walls for the cooperative condition. Additionally, no difference between groups was found for either condition on gaze transfer between View to Play or Play to View walls.

B. Movement Time

The three movement times we observed in this study are shown in Figure 7. We reported movement times for grabbing and placing cubes in our conference paper [1]; however, like the gaze duration measures, individual samples were used for this analysis. Additionally, we have added a new measure to the Figure 7, which is the movement time between participants grabbing and placing cubes.

As shown in Figure 6, the table of unequal variance t-tests compares the three-movement times between groups for solo and cooperative conditions. We found that the non-autistic populations took significantly longer in both solo ($p = 0.01$) and cooperative ($p = 0.007$) conditions to grab cubes. Inversely, autistic individuals took significantly longer to place cubes in both solo ($p = 0.01$) and cooperative ($p < 0.0001$)

Comparison	Condition	Group	Mean (ms)	t	df	p
Grab	Solo	Aut	413051	-2.431	800.24	0.015*
		Non-Aut	454.55			
	Cooperative	Aut	406.76	-2.691	507.27	0.007*
		Non-Aut	465.23			
Place	Solo	Aut	510.39	2.484	1053.1	0.01*
		Non-Aut	465			
	Cooperative	Aut	634.3	4.398	286.32	<0.0001*
		Non-Aut	462.88			
Grab to Place	Solo	Aut	1179.99	0.362	1178.3	0.717
		Non-Aut	1170.9			
	Cooperative	Aut	1334.28	2.484	553.32	0.01*
		Non-Aut	1236.26			
Blink Rate	Solo	Aut	37.22	-0.166	35.376	0.87
		Non-Aut	37.96			
	Cooperative	Aut	27.86	-1.651	36.49	0.1
		Non-Aut	32			

Fig. 6. Unequal variance t-tests comparing movement and blink measures between groups across conditions.

conditions. Autistic individuals also had a significantly longer grab to place movement time in the cooperative condition ($p = 0.01$). There was no statistical difference found between groups for the solo condition.

C. Arousal

The first arousal measure shown in Figure 8 comes from the conference paper [1] and indicates that for the baseline interval (the averaged time epochs less than zero), the percent change in pupil size remains flat, showing that pupil size is relatively flat over the second preceding the grasp event. After the grasp event, the pupil size increases up to 2–5% within about 1/2 second in both groups. In the solo condition, autistic and non-autistic groups show similar increases with no significant differences. In the Cooperative condition, pupil diameter increased faster in the autistic group, and at 1/2 second, the autistic group's pupils had already increased by 5.1% while the non-autistic group's pupils increased by 2.34%.

Figure 9 separates the measure shown in Figure 8 into individual grab and place arousal measures. We compared these separate grab and place events over the same interval examined previously. The response after a grab event showed no difference across group or condition. However, after a place event, there was an increase in both groups' responses in the solo condition, with the autistic group showing a higher overall response. We chose the 0.5–0.6 second mark to perform a two-way ANOVA for the cooperative condition because this segment shows the largest differentiation between groups. The results of this ANOVA showed no interaction between group and hand movement (grab / place) ($F(1, 18) = 1.273$, $p = 0.247$). Simple main effects analysis showed that group ($F(1, 18) = 4.771$, $p = 0.042$) and movement ($F(1, 18) = 58.523$, $p < 0.0001$) did have a significant effect on arousal. Again, both groups showed an increased response, but the autistic group's response in this case was more elevated over the non-autistic group.

D. Blink Rate

To interpret blink rate data, we examined differences between group and condition as shown in Figure 10. The results of the two-way ANOVA found no statistically significant interaction between the effects of group and condition ($F(1, 25) = 0.212$, $p = 0.646$). Simple main effects for blink rate analysis showed that group did not have a statistically significant effect on blink rate ($p = 0.829$). Simple main effects analysis showed that condition did have a statistically significant effect on blink rate ($p = 0.024$), with the blink rate lower in the cooperative condition.

IV. Discussion

The present study aimed to investigate the effects of social presence on gaze behavior, gross motor movement, arousal, and blink rate in autistic and non-autistic participants using a cooperative VR game-based task. For both the autistic and non-autistic groups, we found instances of longer gaze duration and transfer time, as well as longer gross motor movement times. For the autistic group, we found increased arousal relating to gross motor movements in the cooperative condition. No differences in blink rate were shown between groups; however, both groups had significantly shorter blink rates in the cooperative condition compared to the solo condition, possibly indicating greater engagement during the condition that involved another player. The highly dynamic nature of the game required participants to collect complex information and execute behaviors differently depending on in-game demands. To contextualize the measurements found for this experiment, we consider the nature of information gathered from each of the AOIs (Play Wall, Build Wall, and View Wall), as well as the primary mechanics of pattern completion and how they demand individual behaviors when playing the game. Here, we discuss the impact of these game components as well as the effects a social component creates.

A. Gaze Behavior

We designed the game such that different AOIs would influence gaze movements in specific ways to complete the task. Participants were motivated to switch their attention between AOI as fast as possible in order to finish their cube color pattern under the given time limit. Therefore, longer gaze duration and transfer times on and between AOI suggest that participants are performing less efficiently than if those times were shorter. An example of this is demonstrated via a common sequence of gaze behaviors necessary for completion. The sequence starts with looking at a cube before grabbing it on the Play Wall, transferring gaze to the Build Wall, visually locating the correct Drop Zone and placing the gabbed cube into it, transferring gaze over to the View Wall for pattern reference, and finishing by transferring gaze back to the Play Wall to grab another cube. Our analysis separates this sequence into its parts to identify how the different stimuli attached

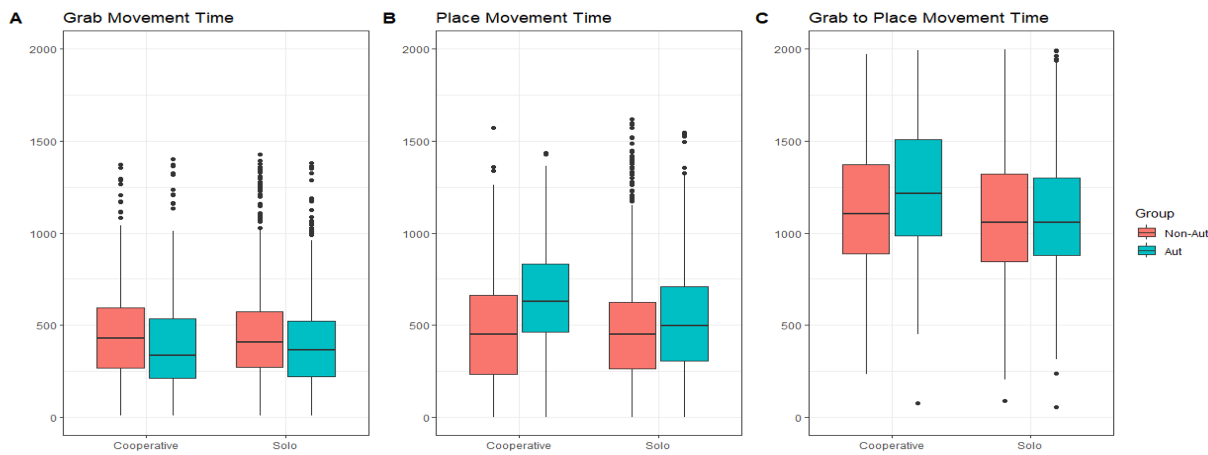

Fig. 7. This shows the Aut (blue) and Non-AUT (red) group movement times for the three measures A) Cube Grabbing, B) Cube Placement, and c) Grab to Place using box and whisker plots. showing the upper and lower quartile of the group's mean fixation duration times. The median of each group's data is indicated by the center line of each box.

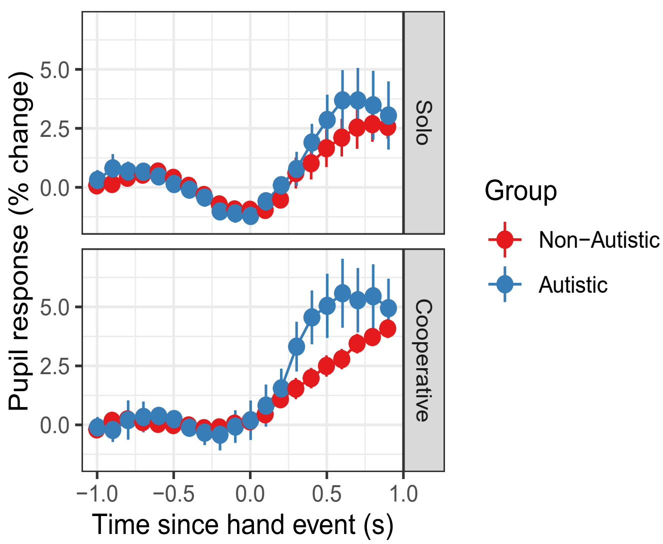

Fig. 8. Baseline-subtracted pupil diameter data triggered on hand event in solo (top) and collaborative (bottom) conditions by group.

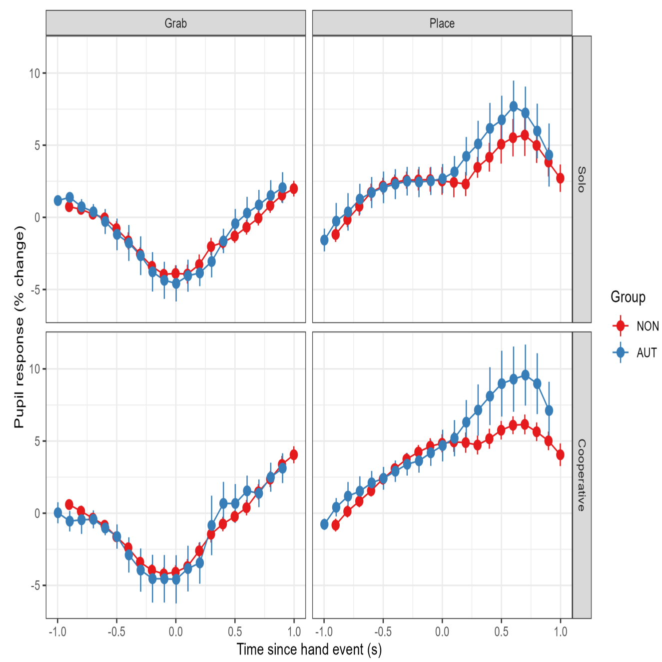

Fig. 9. Baseline-subtracted pupil diameter data triggered on different hand event types (grabbing and placing) in solo (top) and collaborative (bottom) conditions by group.

to each AOI affect players in different groups. In addition to the different in-game requirements, gaze behavior is also affected by the social condition of the game. We hypothesized that autistic players would have longer gaze duration and gaze transfer times on and between AOI. Moreover, higher degrees of dynamic stimuli, including both social and non-social objects, would increase the times from both groups. Our findings for gaze duration on the Play Wall confirm this hypothesis due to the significantly longer time autistic individuals spent looking at this AOI in the cooperative condition. Similarly, autistic participants had significantly longer gaze durations on the Build Wall during the cooperative condition. However, this group difference flipped in the solo condition, and the non-autistic group spent longer looking at the Build Wall, possibly indicating a social condition-based effect. Gaze transfer time between the Play and Build Walls also produced alternating group differences. Transfer from the Play to Build Wall showed autistic participants taking significantly longer in the cooperative condition, and transfer going back from the Build to Play Wall showed the non-autistic participants taking longer in the solo condition. Trends in these gaze duration and transfer time results suggest that the cooperative condition has a larger impact on the autistic group, and the solo condition has a similar effect on the non-autistic group. No difference was found in gaze duration to the Play Wall itself during the solo condition.

We observed unexpected results for gaze duration on the View Wall. We found that autistic individuals had significantly shorter gaze duration in the solo condition, indicating that this group was able to obtain the information needed from this wall more effectively than the non-autistic controls. There is potential evidence to explain this result based on studies that have examined visual search speed in autistic individuals [45] as well as strength in block design tasks [46]. Of the three walls, interaction with the View Wall most resembles aspects of a static visual search or block design task. For both of these traditional tasks, as well as optimal use of the View Wall within the game, participants must visually search for and find the part of the pattern that they need to complete their Build and then transfer their attention back to the Play Wall to find that cube. We observed no differences in transfer times going from the Play to View Wall or vice versa, but we largely attribute this to the shortness of distance between these AOI. Although similar in many ways, the differences in result for each Wall combined with the inclusion or exclusion of a virtual presence affected the participants' use of gaze behavior.

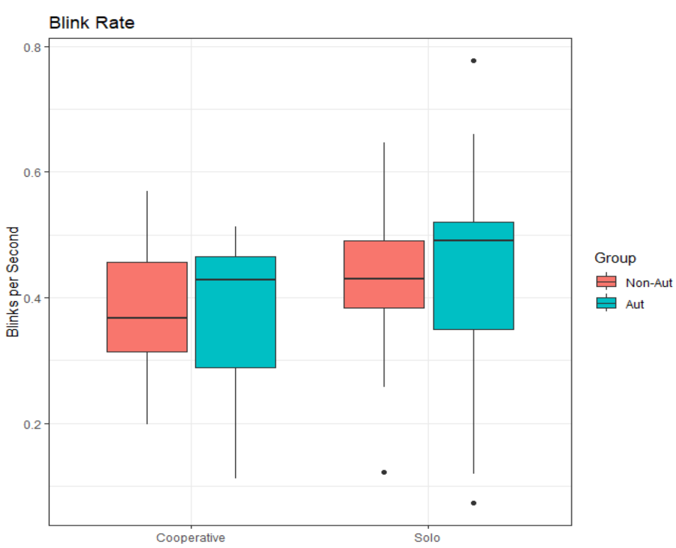

Fig. 10. Blink rate in blinks per second shown for each group (non-autistic in red; autistic in blue) and condition as box and whisker plots.

The Play Wall contained the most dynamic and socially salient stimuli of the three walls. Unlike the Build and View Walls, the interactive elements (the cubes) on the Play Wall were moving, and participants had a direct line of sight with the virtual presence of their cooperative partner (see Figure 2 for reference). Efficient use of gaze while on the Play Wall required participants to visually search between the moving cubes for the correct color, incorporate a gross motor action to catch that cube, and then direct their attention to the next AOI. We designed the Play Wall to stress the participant's ability to use gaze and movement functionally while also being subject to their partner's movement-based social cues. Performance on the overall game objective required participants to fluidly integrate the highest degree of spatiotemporally dynamic stimuli on the Play Wall. This included non-social moving block stimuli and the social image of a partner in the cooperative condition viewed through the Play Wall. We predict that the salience of the moving stimuli compounded with the direct visual line to the partner's virtual presence and incorporation of gross motor movements is why we see an increased fixation duration for autistic individuals in the cooperative condition on the Play Wall. This claim is supported by the Play Wall results for the solo condition, where there is no virtual presence, and shows no significant difference between groups.

Similar to the Play Wall, The Build Wall also requires the integration of movement and efficient interaction. Although not as visually salient, social consideration is necessary when placing cubes collaboratively onto the Build Wall, but there are fewer temporal dynamics compared to cooperatively grabbing moving blocks from the Play Wall. Both Walls are similar in requiring gross motor interaction, and both Walls require participants to visually search for individual stimuli, a cube for the Play Wall and Drop Zones for the Build Wall. Comparing the gaze duration results of the Build and Play Wall reveals a difference in group performance in condition. This difference implies that autistic individuals' gaze behavior is impacted by their social presence when looking at the Play Wall and the Build Wall.

B. Gross Motor Movement

In this study, we examined three gross motor movements (described II.E section above) that players used over the course of playing the game. Grabbing and placing cubes required an initial visual identification of an object (cube for grabbing and Drop Zone for placing) and a subsequent gross motor movement responding to that object. The third movement we examined was the movement time, starting the instant a cube was grabbed on the Play Wall and ending when that cube was placed into the Build Wall.

Our hypothesis that autistic individuals would perform slower on gross motor movements was only partially supported for these three measures. The autistic participants took significantly longer to place cubes in both conditions, and they also took longer to transfer cubes from the Play Wall to the Build Wall in the cooperative condition. No difference was found between groups for transferring cubes from the Play to Build Wall in the solo condition. Analysis of the grabbing movement also proved our hypothesis incorrect, showing that the non-autistic group took significantly longer to grab cubes on the Play Wall in both conditions.

Similar to the results for gaze behavior, we see an increase in movement time (see Figure 7) in the cooperative condition among autistic players in two of these movements, namely Place and Grab-to-Place. It is unclear as to why the results differed for Cube Grabbing, however, where autistic players are faster overall, including in the cooperative condition. One possible explanation for this result is a lack of motor complexity demanded from the game. We noticed during data collection that grabbing moving cubes from the Play Wall was not as challenging as we had tried to make it. The cubes moved very slowly in a singular direction and with no changes in depth. Due to the mechanics of the laser extending the reach of the player's grasp, participants simply had to move their wrists slightly to grab a cube. Potentially, this lack of sophistication in movement is the cause of our result. The cube placement required more complexity in gross motor movement as participants had to rotate their torso to face the Build Wall and use precise upper-limb coordination to place cubes into the desired Drop Zone. If the game-based task design is not the reason for this result, then our findings go against previous research asserting that autistic individuals have difficulty executing movements involving temporally dynamic stimuli.

C. Arousal

This study was designed to evaluate changes in arousal in relation to both gross motor movement and social stimuli. While it is unclear in the literature as to why both hypo and hyper-arousal have been recorded for autistic individuals attending to social stimuli [37], this was, to our knowledge, the first study to measure arousal in relation to gross motor movement with a social variable. As was observed in our prior work [1], Figure 8 showed that after upper-limb gross motor actions, autistic individuals had a significantly larger increase in pupil size than non-autistic controls in the cooperative game condition. We also separated the two gross motor actions in Figure 9 and determined that the placement of cubes was responsible for this increase in arousal. Our measure of cube placement movement time mimics this conditional result. It is possible that increased arousal after the placement of a cube is related to the increased amount of time that is taking autistic players to complete the transfer from the Play Wall (cube grab) to the Build Wall (cube place) in the cooperative condition. Additional work needs to be done to understand why movement and social presence are contributing to this hyper-arousal response in autistic players. Understanding the impact that motor and arousal measures in autistic players have on social interaction could also be important for understanding social interaction in general.

D. Blink Rate

Our study also examined blink rate during a dynamic interaction–which offers a novel way to examine blink response. Relatively little research exists on the effects of social stimuli on blink rate in autism. As such, our exploratory research in this area was conducted without prior expectations. We observed that for both groups, the cooperative condition showed lower blink rates, which may indicate greater engagement. This is an interesting finding, especially in light of the prevalent autism social motivation hypothesis [47], which proposes that autistic individuals have a reduced amount of engagement in social situations. More work needs to be conducted using this measure in an expanded set of conditions to better understand the meaning of these results.

V. Virtual Presence

We sought to design and implement a fun, interactive, and intuitive game that would allow us to manipulate aspects of movement and social presence in a controlled environment. Our gameplay is not as predictable as in traditional (i.e. not game-based) experimental designs, but also not a "gamified" task. Gamification is often used in different contexts including experimental studies to generate additional engagement for a task or application that might otherwise not be as interesting for users. Unfortunately, many such "games" used for scientific research are no more than standard laboratory assessments with better graphics. This is minimally helpful in engaging the participant through the duration of the task and does not produce the dynamic immersion needed to extract what we seek in terms of naturalistic behaviors. We sought to create a game that is truly immersive and measures intrinsically motivated behaviors that are built into the game's design. This intrinsic approach increases the validity of the participant's data and eliminates potential confounds related to task design. It also increases the variability in behavior because the dynamic nature of the game affords participants a degree of freedom to create their own unique strategies.

We believe that the results of this study show a representation of the kinds of behavioral responses that autistic and non-autistic populations would use when dealing with similar dynamic situations involving a social presence in the physical world. The virtual social presence in this cooperative version of this task was believed to have impacted both autistic and non-autistic groups in gaze, gross motor movement, arousal, and blink rate. However, The effect of a virtual presence was more pronounced in the autistic population, with the majority of differences discussed here being found in that population. We hypothesized that a social virtual presence would have a larger effect on the autistic population's use of gaze and movement, and their physiological responses of arousal and blink rate. We established these predictions based on autistic symptomatic challenges with social interaction, as well as the documented irregularities in gaze, gross motor movement, and blink rate. Studies attempting to connect social interaction to these individual differences in autism using both social and non-social conditions often include additional human stimuli in either video or photographic forms [19], [20], [38]. Neither these studies implementation of social conditions nor the virtual social presence used in our study constitute a real social interaction; however, the similarities in result compared with the differences in methodology could suggest something about the nature of autistic difficulty with social interaction. Although the virtual presence used in this study is not recognizably human in appearance, the inclusion of the virtual body, just like the inclusion of the humans in the video or photographs, produces similar differences in timing for behavioral functioning and autonomic response. Potential explanations for this could be related to the cognitive complexity of social interaction in general or the visual complexity of the included stimuli. This will be a key focus of future research in autism, because precisely identifying what components facilitate these differences is an essential component for understanding challenges in social interaction. While this game accomplished many of the goals we had set out to investigate, it only provides early clues about the kinds of effects that different social and non-social stimuli have on behavioral responses in a dynamic interactive environment.

VI. Conclusion

Our aim with this study was to use this fully immersive VR video game to characterize several components that are fundamental to social interaction. We used gaze behavior, gross motor movements, arousal, and blink rate to characterize responses in solo and cooperative play conditions. Among autistic players, we observed differences in different aspects of each of these domains compared to non-autistic controls. We also found that a social presence had an effect on gaze, gross motor movement behaviors, arousal, and blink rate in non-autistic players, although not to the same degree that the autistic group displayed. The IEEE Conference on Games debuted the first version of this study [1] presenting initial results for gaze, movement, and arousal. In this paper, we have expanded each of those domains to include measures of gaze transfer Figure 5, an additional measure of gross motor movement Figure 7, and a more in-depth analysis of our primary arousal findings Figure 9. Additionally, this paper also presents an additional examination of blink rate Figure 10. Future work will improve this paradigm for determining the effects of virtual social presence on users, and we will also attempt to characterize competitive versus collaborative social interactions.

VII. Limitations

Despite the insights gained from this study, we want to acknowledge several limitations that should be considered when interpreting the findings. Firstly, we did not collect any symptom severity or detailed diagnosis data. Therefore, we cannot determine if autistic symptoms are correlated to any of our observed measures. Secondly, randomization of condition trials and additional patterns must be added to remove any practice effects that occur by the end of the final trial. Third and lastly, we were not able to measure the amount of time the participants were directly observing each other due to the Play Wall blocking the line of sight. This could be a crucial measure in determining group differences moving forward. We hope to continue this work and make all necessary changes for the next iteration of the game.

VIII. Future Work

In future studies, we will hone our game design to better control the conditions for measuring behavior. Specifically, the virtual presence that was used in this study was visually unrealistic compared to a person. It would be interesting to see if behavioral responses change based on the degree of realistic detail of the social presence. Similarly, with the non-social stimuli, the range of dynamic movement of the cubes on the Play Wall was one potential issue with our movement measurement of cube grabbing. In a future version of this game, we will vary the speeds and angular movement of the cubes to systematically gauge how the rate of speed and angular trajectory affect gaze and motor behavior. This is more in line with gross motor movement research indicating disrupted ball-catching behavior in autistic participants likely due to the demands of interpreting and planning actions for a spatiotemporally dynamic stimulus. To learn more about the specifics of social interaction and the effects that a virtual social presence has on the behaviors of individuals, we will use the data we gathered from this game and implement it into the next iteration of our game design. This study is a foundational step in creating dynamically social games capable of measuring an array of sensory motor signals. This step will be a necessary jump in the field if we want to study how humans are changing behaviorally and physiologically in response to different social or non-social environments. The environment that we have created is set up to capture multiple different types of signals in addition to the ones we have documented here; heart rate and lower body movement analysis could be valuable additions. Here, we have just begun to start using the environmental control that VR allows, but in the future, this process will be more refined. This control, combined with the engagement that gamification affords, will allow us to elevate our research beyond what is currently being done.

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