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ASSESSMENT OF SENSORY ABNORMALITIES IN CHILDREN WITH ASD USING VIRTUAL REALITY

by

Ankit Koirala

A Thesis Submitted in
Partial Fulfillment of the
Requirements for the Degree of

Master of Science
in Engineering

at
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ABSTRACT

ASSESMENT OF SENSORY ABNORMALITIES IN CHILDREN WITH ASD USING VIRTUAL REALITY

by

Ankit Koirala

The University of Wisconsin-Milwaukee, 2019
Under the Supervision of Professor Brian Armstrong

Sensory abnormality is one of the important characteristics of Autism Spectrum Disorder(ASD). A large number of studies suggest a strong connection between sensory abnormalities and ASD. Therefore, it is important to assess sensory abnormalities for diagnosis and intervention of ASD. In this thesis study, we aim to develop a virtual reality system that can measure sensory abnormalities in adolescents with ASD. Sensory abnormalities can affect all five senses: touch, vision, smell, taste and auditory. However, in this study, we focus on assessing sensory abnormality in vision and touch sensory processing. Twelve adolescents with ASD and 12 typically developing (TD) adolescents aged 11-17 years participated in the study. Participants were assigned a task in which they interacted with the virtual reality system. The system recorded participants' behavior and their response to the virtual environment in the real time while they completed the task. We defined four measurements to analyze the behavior of the participants. With the help of the defined measurements, we found some significant differences in the way participants with ASD and TD participants interacted with the virtual environment. Participants also filled a commonly used standard psychological assessment questionnaire called

Adult/Adolescent Sensory Profile (AASP). Strong correlations between some of the scores in the questionnaire and their response to the virtual environment were also observed. Therefore, this pilot study supports the use of technology to assess sensory abnormalities and shows that further research into the development of such technology is essential.

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ACKNOWLEDGMENTS

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1 Introduction

Autism spectrum disorder (ASD) is characterized by difficulty in communication and social interaction, often accompanied by repetitive behavior, which may not be evident up until it starts to impede social, occupational and other normal aspects of life [1].A study conducted by Korgan et al. [2] estimated that around 673,000 children in the United States had ASD. Therefore, it is a common disorder which has a profound impact on the life of an individual. However, diagnosis of ASD is not an easy task because often it’s not easy to pinpoint autism spectrum based on a single psychological or behavioral phenomenon [3]. Although, impairment in social communication and repetitive behavior are common traits of ASD, there exist a large variation in severity of those traits and intelligence [4]. Diagnosis of autism requires a long and complicated psychological profiling and testing, using psychological instruments. Technology, especially, Virtual Reality (VR) has been increasingly investigated for ASD intervention, but few studies have focused in using this technology in assessing and studying sensory abnormalities in relation to ASD and its diagnosis.

Diagnostic instruments called Autism Diagnosis Observation Schedule (ADOS), which comprises a number of different modules, is widely used for the diagnosis of ASD [5]. Most of the common instruments and questionnaires rely on the impairment of social interaction and verbal communication skill to assess ASD [6]. Despite being quite successful these instruments do suffer from some limitations. Evaluation from questionnaires and observation are inherently prone to subjective biases. Questionnaires also have limited resolution in the sense that the large variation across the autism spectrum cannot be precisely assigned to a few discrete numbers. Motivated by these factors, our study is designed to attack the problem from a different angle- Using technology to assess sensory abnormalities in individuals with ASD and find relation between sensory abnormalities and ASD. Many literatures has studied the prevalence of sensory abnormalities in children with ASD. Research done by Lars Klintwall et al. [7] on sensory abnormalities in children with ASD aged 20-54 months showed sensory abnormalities was a common trait in them. Sensory abnormalities are found to be correlated with the stereotypical repetitive pattern of behavior in ASD[8]. Therefore, sensory impairments have been included in the latest autism diagnostic manual (DSM-5) [9].

1.1 Sensory Abnormalities and ASD.

Sensory abnormality is a condition in which people can be hyper sensitive or hypo sensitive to stimuli [10], [11]. The sensory abnormalities is prevalent in children with ASD and was added as a diagnostic criterion of ASD in the DSM-5 [9]. People with sensory abnormalities can either be overwhelmed by senses like touch, hearing or visual stimuli or not response properly to the stimuli. Sensory abnormalities in children with ASD is so common that it has been reported in more than 90% of the population [12]. Moreover, some studies [12], [13], [14] claim that the sensory profile of children with ASD is, typically, different from typically developing children. All five major sensations have been found to be affected by the sensory abnormalities including kinesthetic and proprioceptive sensory modalities [11] We have designed our study to focus on two sensations: touch and vision.

A research [8] found that stereotypical behaviors and interests in children with ASD are significantly related to sensory symptoms. The same study also showed that the sensory impairments is more common in ASD than other developmental disorder. A study [15] found that multiple sensory abnormalities were found in more than 90% of children with ASD. Sensory abnormalities in taste, smell and vision being the most common differences between children with ASD and typically developing children. Sensory symptoms have also been found to be affected by age and IQ of an individual with autism [15], [16]. Freeman et al. [16]. studied the effect of IQ on the assessment of the disorder based on the behavior pattern. They found that a large difference exists in behavior pattern, when we compare the difference between high IQ children with ASD and TD children whereas, less so when we compare the difference between low IQ children with ASD and non-autistic children with mental retardation. Some study [17] suggests that the stereotypical repetitive behavior pattern might be the result of impaired sensory integration in people with autism due to sensory abnormalities, since, learning, coordination, and adapting are results of effective sensory processing and integration. It is also believed that poor social and communication skills is the effect of poor sensory modulation [18]. Dunn & Kientz [19] used sensory profile to assess the difference in behavior of children with ASD and TD children. They found that the two groups differ in most of the items in their sensory profile. Furthermore, even for the items that were common among both groups the distribution of the items was different. They, further, suggests that more comparative studies on children with sensory disorder can be helpful to find a method to distinguish children with ASD and their TD peers.

Our study takes motivation from a large number of previous studies that showed a tangible connection between sensory abnormality and ASD. The primary point of this thesis study is sensory processing difference in tactile and visual sensory domains between adolescents with ASD and TD adolescents. Touch sensitivity is a commonly reported sensory abnormality among children with ASD. Marco, Hinkley and Hill [20]. found a correlation between a certain measure of touch sensitivity and social reaction. High sensitivity to touch stimuli can cause a person to refrain from social interaction involving touch [21]. However, O'Riordan and Passetti [22] devised a study to compare the tactile sensitivity of TD children and children with ASD, and their result showed no difference between the two group at all. Wiggins et al. [8] conducted a similar study to find the difference in sensory abnormalities as a distinguishing feature between the two groups. They claim that children with ASD have more tactile sensitivity than children with other developmental disorders. Also, they found a correlation between the repetitive behavior pattern and their tactile sensitivity. Finally, they concluded that tactile sensory abnormalities can be used as a distinguishing factor for children with ASD. Blakemore et al. [23] studied the tactile sensory profile of a group of TD children and children with ASD and drew some interesting conclusion that there was no significant difference in threshold of detection and methods of coping the stimuli between the two groups. Their findings suggest that the difference in tactile sensory profile might be more emotional in nature than physiological. Cascio et al. [24] measured and compared tactile sensitivity in adult with ASD and adults without ASD. This work did not report any abnormal perception in adults with autism, but they noted higher sensitivity among adult with autism for thermal sensation and low frequency vibration in certain areas of body [24]. Study by Minshew and Hobson [25] reported significant difference in self reporting of the sensory sensitivity between groups of people with and without ASD aged between 8-54 years. They also found sensory abnormalities in higher cortical perception in ASD. However, the groups did not display significant sensory perceptual difference [25]. They also drew the conclusion, similar to that of Blakemore et al. [23], that the difference in observed sensory responsivity might be due to the difference in emotional response to the stimuli. Regardless of the origin of the difference in their response, however, the difference should be noticeable as long as it is reflected by their action. Therefore, new studies on tactile sensory abnormalities are needed to further answer the long-standing question of whether a specific touch sensation pattern can be found to distinguish children/adolescents with ASD from TD children/adolescents.

Similarly, large number of studies have shown connections between visual sensory abnormalities and ASD. Baruth et al. [26] studied the visual sensory abnormalities in children with ASD, and observed higher cortical responsivity to visual stimulus in children with ASD than that of control group, irrelevant to the tasks given. They also pointed out that a higher sensitivity to visual stimulus at early stage of processing may hamper the individual's ability to discern necessary information from irrelevant ones [26]. Another study by Falter, Elliott and Bailey [27] examined temporal resolution of adolescents and adults with and without ASD. The study revealed that the threshold for visual stimulus was lower for individuals with ASD compared to neurotypical individuals. The study also found decreased capability in individuals with ASD to integrate visual signals over time. Thus they concluded that individuals with ASD have better capability to focus on the details, but they are impaired in creating a bigger picture by generalizing the visual information compared to typically developing individuals.[27]. Dakin and Frith [28] conducted research on visual perception in individuals with ASD and drew similar conclusion. They concluded that individuals with ASD were better at processing fine details in visual stimuli than TD individuals, however, whether individuals with ASD were worse at processing global visual information was not clear. Dakin and Frith [28] also suggest that abnormalities in superior temporal sulcus may explain abnormalities in visual perception such as motion processing and that may relate to impaired social skills in children with ASD [28]. Koh, Milne and Dodkins [29] defined four measures to measure and compare the visual contrast sensitivity of adolescent with ASD and TD adolescent at seven different spatial frequency (0.5-20 cycles/degrees). Their study did not find any significant difference between the two groups in any of the four measures.

However, the study suggested impaired contrast detection for some specific signal/noise ratios in children with ASD. Various studies have linked visual impairments in ASD to social and communication impairments in different ways. Some researchers attributed visual impairment as the cause of social and communication impairments, whereas some other researchers believed that individuals with ASD were unable to interpret visual information due to lack of social and communication skills [30]–[32]. Researchers have also studied the effect on the responsivity to visual stimuli in children with ASD for different spatial frequency and compared it to a TD group [23]. No significant difference was found. Nonetheless, visual impairment has always been a common and interesting part of ASD. Hence, investigation of visual impairment to assess the sensory abnormalities that differentiate children with ASD from TD is essential.

VR is widely used for studying ASD. Goldsmith and LeBlanc [33] has noted the increasing use of VR in studies related to ASD[33]. They attribute control over environment and accuracy to the increasing use of VR for research purpose. Wade et al. [34] developed a virtual reality based driving simulator to assess and compare the behavior and physiological VR system was effective and precise enough to reflect subtle differences, such as differences in gaze patterns, between adolescents with ASD and TD adolescents. by developing VR system that includes sources of visual and touch stimulus we are able to observe and measure the response of adolescents with ASD to the stimulus and those of their TD peers. The differences between the two groups may provide a special view to understand the sensory abnormalities in adolescents with ASD.

1.2 AASP

Assessing sensory abnormalities is the goal of our study. Therefore, it is essential that we have an established measure that findings of the study can be compared against; Adolescent/Adult

Sensory Profile (AASP) serves that purpose. “The Adolescent/Adult Sensory Profile is designed to promote self-evaluation of behavioral responses to everyday sensory experiences. It provides a standard method for professionals and individuals to measure and to profile the effect of sensory processing on functional performance” [35]. AASP is based on Dunn’s model[19] that categorizes sensory processing into four behavioral patterns due to interactions between neuroscience and behavioral concept [36]. Neuroscience concept consist of the neurological threshold continuum divided into two parts *High Threshold* and *Low Threshold.* Lower the neurological threshold the higher the individual is likely to detect and react to stimuli [35]. Behavioral concept consists of behavior response continuum divided into two categories, *Passive Behavior* and *Active Behavior*. Behavior response continuum tells individual’s response towards the stimuli in according to their neurological threshold [36]. Passive behavior refers to the passive responses towards stimulus in which no attempts are made to alter or control stimuli. Whereas, active behavior indicates that the individual engages with the environment in an attempt to control the stimuli [35]. The interaction between neurological threshold continuum and behavioral responses give four different behavioral patterns knows as sensory-processing-pattern. These patterns are called Low Registration, Sensory Seeking, Sensory Sensitivity and Sensory Avoiding [35].

Table 1.1 Sensory-Processing-patterns

		Behavioral Response Continuum	
		Passive	Active
Neurological Threshold Continuum	High	Low Registration	Sensation Seeking
	Low	Sensory Sensitivity	Sensation Avoiding

Low registration entails that the individuals are less sensitive towards a stimulus and they may miss or not respond immediately. Individuals with sensation seeking behavior enjoy stimuli and seek additional sensory stimuli. Sensory sensitivity means that the individual finds stimuli discomforting and respond readily to sensory stimuli. Individuals with sensation avoiding actively engage with their environment to reduce sensory stimuli [36]. Each question in the AASP belongs to one of these four categories and includes five options to answer. The options are almost never, seldom, occasionally, frequently and almost always. Each answer is scored according to the weight of the response. Almost Never = 1 point, Seldom = 2 points, Occasionally = 3 points, Frequently = 4 points and almost always = 5 points. Finally, all the points are added to get the total score for each of the sensory processing pattern.

For this thesis study, the sensory-processing categories that were most relevant to us were touch processing and visual processing. It is important to notice that several studies reported a significant correlation between ASD traits and AASP scores [37], [38]. however, the exact relationship between ASD traits and AASP scores of an individual is still not clear [30]. Stewart et al. [38] found differences in behavior between individuals with ASD and TD individuals in every quadrant of the AASP for different age groups. The ASD group scored higher in low registration quadrant and lower in sensation seeking quadrant than the TD group [31]. Marche, Steyaert and Noens [13], a similar psychological study to this, compared sensory profile of adolescents with ASD and without ASD and found that adolescents with ASD scored higher in sensation avoidance quadrant and lower in sensation seeking quadrant [27]. In contrary, a study by Kern et al. [39] found that individual with ASD tended to avoid sensation stimuli more than non-ASD individuals [39]. Moreover, Kern et al. [40] found that the degree of correlation between ASD traits and their sensory score was age dependent, and the correlation reduced with age. The correlation between severity of autism and their sensory score was stronger in younger children than adolescents[40]. Although, studies drew different conclusions regarding the relation between sensory scores and ASD, most of the study were successful in linking sensory profile with ASD in one way or another. Nonetheless, our study intends to uncover ASD traits and find differences between adolescents with ASD and TD adolescents using the data obtained from both the system and AASP score. AASP is relevant to our study as it can help explain and/or validate findings inferred from behavior data collected from VR system.

2 System Development

Given the nature of relation between sensory abnormalities and ASD, as described in the previous section, we expect seeing differences in the response of individuals with ASD and TD individuals to the same set of stimuli. Hence, we construct a VR system that participants can interact with and that also provides visual and touch stimuli to the user. The system has two components

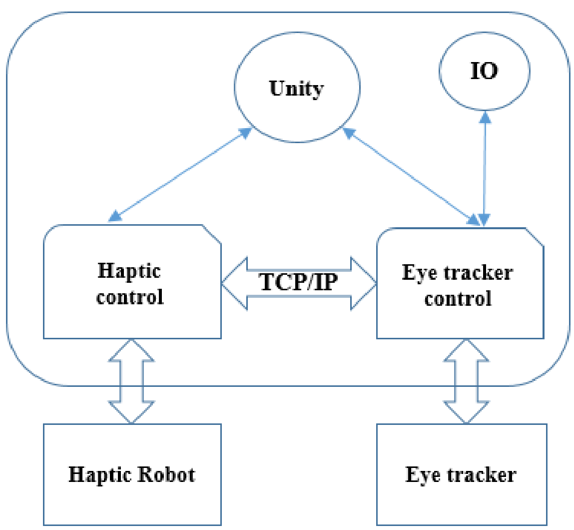

Figure 2.1 System Diagram

1.) Physical Components: Physical components are the components, through which users interact with the VR environment. This includes a computer, a haptic robot and an eye tracker (Tobii Pro X-30) [41]. Physical components also include software components which are Unity (a commercial game engine) [42] and programs developed using C# and Python programming languages. C#, being a native language to Unity, is used to develop programs to control the game and also the haptic robot. Programs developed using python is used to operate the eye tracker and manipulate Input/Output (IO) and files on the computer.
2.) VR Environment: The virtual environment consists of 12 different scenes. Each scene consists of an arrangement of bars, a ball that the players can move using the haptic robot and multiple distracting objects. The virtual environment provides the basis for the touch and visual stimuli. Users are able to receive touch stimuli when they touch the bars in the scene with the ball. The distraction present in the scene provides visual stimuli to the users together with the bars.

2.1 Physical Components

There are two sources of data in the system; a Haptic robot (Touch by 3D systems) [43] and an eye tracker (Tobii Pro X-30). Haptic robot provides the data that shows the movement of the ball

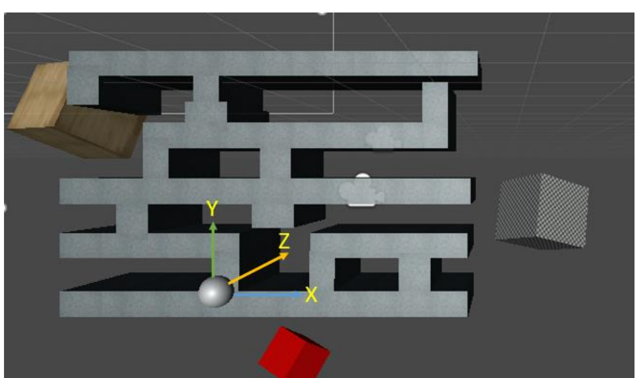

Figure 2.2 World Coordinates

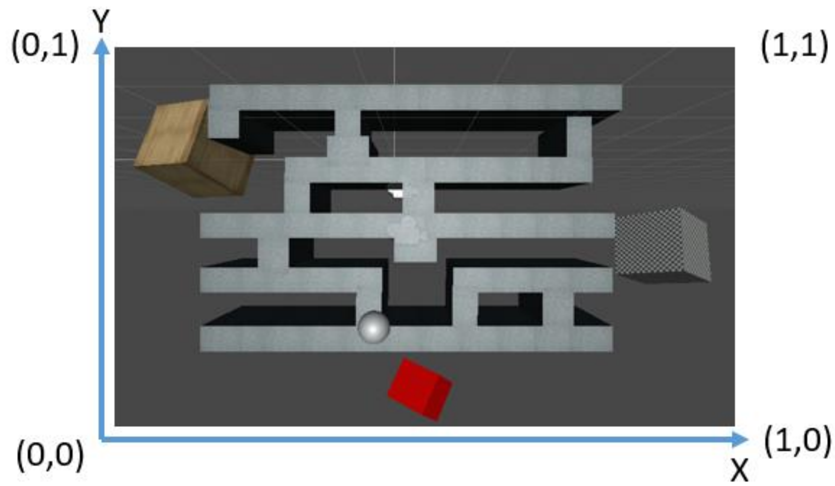

Figure 2.3 Viewport coordinates

in terms of 3 dimensional vector in world coordinates. World coordinates spe c ify the location of objects in the scene. To convert the location of the objects in the scene to the location on the screen, we convert the data points in the world coordinates to normalized viewport coordinates which is a 2D coordinate system. In viewport coordinate the bottom-left corner of the screen has coordinates (0,0) and the top-right corner of the screen has coordinates (1,1), regardless of the size and resolution of the screen. The eye tracker sends stream of data which are coordinate values of the point on the screen the player is looking at. Initially these coordinates are in eye trackers' users coordinate system which is again converted to viewport coordinates for the purpose of simplicity and uniformity. Eye trackers user coordinate system is similar to viewport coordinate system except that the coordinates of top-left corner of the screen is (0,0) and bottom-right corner has coordinates (1,1). The eye tracker is a 30Hz eye tracker that means it scans and tracks gaze movement of the user and provides the coordinates values 30 times per second. However, the frame rate for the game is set to 60Hz for smooth gameplay. Since, the haptic device is also controlled by the same set of programs as the game itself, it also sends data at the rate of 60Hz. Therefore, the two components of the system are not in sync. In the system, once the eye tracker successfully collects a valid gaze data point, it triggers the program that controls the haptic device to save the coordinates of the current position into a file. This arrangement ensures that both gaze and movement data recording were started at approximately the same time.

2.2 The Virtual Environment

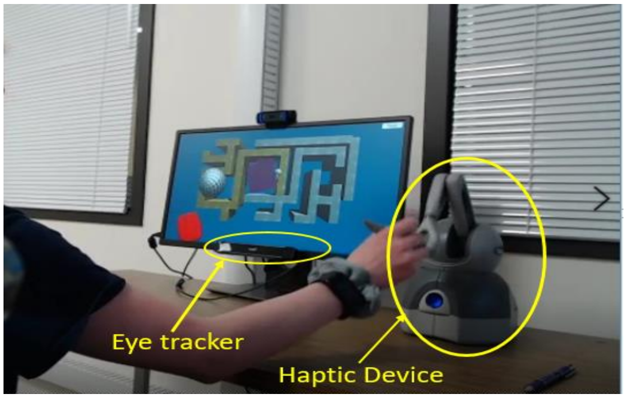

Figure 2.4 System Setup

The system development is centered around the idea that adolescents with ASD may show atypical sensory differences that can be uncovered by means of interaction with the virtual reality system. The game developed using Unity engine acts as a point of interaction between the users and the system. The game consists of 12 different levels. Each level is either 2D in nature i.e. with no depth perception on the bars or 3D, i.e. bars are displayed in with depth information. Users slide the painting ball, as shown in Figure 2, against the bars that turns the bars into yellow. Each level is finished when the user finish painting the bars without leaving any spot.

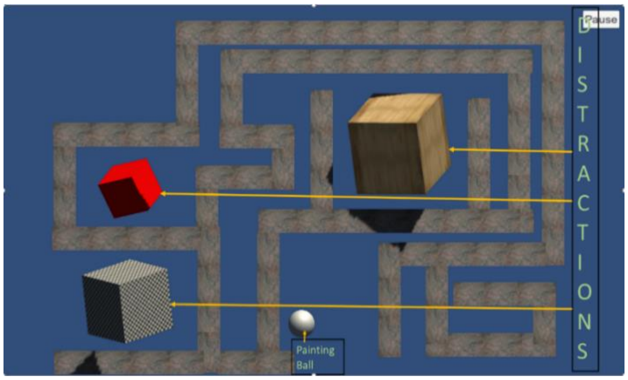

Figure 2.5 A level of the game (2D)

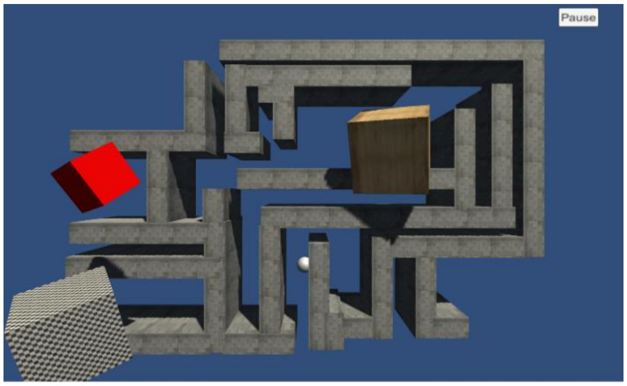

Figure 2.6 A 3D level in the game

Two different type of game scenarios i.e. 2D and 3D will help us to assess how the depth information will affect the game play of the participants. Similarly, the spinning objects are additional source of visual stimuli in the scene that will help us to observe the response of the participant to visually distracting stimuli.

Friction: The friction parameter can be set with a real number from 0-1. The higher the value of Friction the higher the friction the user will feel sliding the ball against the bar. The system allows to have different values for dynamic and static friction. Dynamic friction is the friction experienced by the body when it in motion whereas, static friction is the friction opposing the motion when the body is in rest.

Constant force: Constant force is independent of the position of the ball and its velocity. Therefore, it can act as a gravity, giving weight to the ball. Viscosity: This parameter determine force that is proportional to the speed and is in opposite direction to the motion of the ball. Hence, it allows to set the viscosity of the 'air' in the scene. Higher viscosity means that user will fell higher drag moving the ball in the scene.

Therefore, by changing those parameters, we can change touch stimuli and observe the response of the user in terms of change in their behavior while they play the game.

3 Experimental setup

3.1 Participants

Table 3.1 IQ and ADOS of the participants

ID	IQ full scale score	ADOS total score
1	117.00	3
2	133.00	14
3	126.00	7
6	114.00	16
7	129.00	10
8	89.00	18
9	124.00	8
10	99.00	13
11	59.00	999
12	116.00	15
Mean	110.6	11.555

The study is developed to assess and compare the sensory differences between typically developing adolescent and adolescent with ASD. Therefore, data from both adolescents with ASD and TD adolescent at similar age distribution was desired. In the study, 12 adolescents with ASD (11 males and 1 female) and 12 typically developing adolescents (6 males and 6 female) participated. For participants with ASD, the average age and standard deviation were 14.25 years and 1.587 years respectively. Whereas, for the TD participants the average age and standard deviation were 14.5yeras and 2.179 years respectively.

All of the participants with ASD were diagnosed with ASD based on DSM criteria. Their IQ and ADOS scores were also collected. IQ and ADOS scores for the ASD participants indexed as ASD-04 and ASD-05 were not available.

3.2 Tasks and protocol.

The study was approved by the institutional review board (IRB) of the University of Wisconsin-Milwaukee. The experiment was carried out in the following manner.

- Participants first filled up a sensory profile questionnaire (AASP). The questionnaire consisted of question about the individual's daily experience on taste/smell processing, movement processing, visual processing, touch processing, activity level, and auditory processing. They could consult their parents or the researchers in case they were stuck or confused by the question. This step took about 15-30 minutes.
- Participants played the first level of the game as practice. They could practice playing the game as much as they want during this time. This allowed them to get comfortable and get familiar with the game and the setup. This step was also necessary for eye tracker calibration. The position of the player was better to be determined before starting to collect accurate gaze data.
- The game was restarted and the participants played the game on their own. They played the game by operating a pen-like stylus on the haptic robot. They would see the bars, a virtual ball, and some static or rotating objects. Using the stylus, they needed to press and slide the ball against the bars. If the ball touches a block on a bar, the slid portion of the block was painted into yellow. They would feel some resistance and vibration when

moving the pen. They were told that objective of the game was to completely paint all the blocks as quickly as possible

- Screen was recorded while the participants were playing the game. The data obtained from haptic device and the eye tracker were logged in a file while they played the game.

4 Measurements defined for data analysis

The data obtained from the eye tracker and the haptic robot is in the form of coordinates that specify a position on the screen or the VR system. Four measurements are defined accordingly to generate meaningful interpretations for data analyses.

Performance: Performance measures how fast were participants able to complete the task. The task was into 12 independent levels. Each level has different length of bars to be painted in order to complete the level. Hence, some levels takes more time to finish than others. Therefore, the length of bars of each level needs to be considered to measure performance. Accordingly,

performance is defined in the following way.

$$Performance = \frac{Number\ of\ pixels\ painted}{Total\ Time\ taken}$$

Here, we have measured the length of bars in each level in terms of the number of pixels needed to be painted in order to complete the level.

For individual levels, ‘performance’ is given by

$$Performance\ in\ level\ l = \frac{Number\ of\ pixels\ in\ the\ level}{Time\ taken\ to\ finish\ \ the\ level}$$

And average performance for the entire game is calculated as:

$$Average\ performance = \frac{\sum_l Number\ of\ pixels\ in\ level\ l}{\sum_l Time\ taken\ to\ finish\ the\ level\ l}$$

Therefore, performance has unit pixels/seconds

Gaze Ratio: To measure the response of the participants to the distracting objects on the screen, a measurement called 'Gaze ratio' is defined. This measurement tells what fraction of the total gaze points lies in the distraction region. Distraction region is a rectangular region that tightly surrounded the distracting objects. Gaze point that falls in the region can be expected to be due to the distracting objects. Similar to performance, number of gaze points in any level depends on the time spent on playing the game by the player. Because the system wrote gaze points at almost a constant rate (30Hz), the number of gaze points was also influenced by the length of game play. Therefore, gaze ratio is defined as a normalized measurement to cancel out the length of game play,

$$Gaze\ ratio = \frac{Number\ of\ gaze\ points\ in\ the\ distraction\ regions}{Total\ Number\ of\ gaze\ points.}$$

Similarly, for any specific level, "Gaze ratio" is given by

$$Gaze\ ratio\ in\ level\ l = \frac{Number\ of\ gaze\ points\ in\ the\ distraction\ regions\ in\ the\ level}{Total\ number\ of\ gaze\ points}$$

Also, to calculate the average gaze ratio of a participant for the entire game,

$$average\ gaze\ ratio = \frac{\sum_l Number\ of\ gaze\ points\ in\ the\ level\ l}{\sum_l total\ gaze\ points\ in\ the\ level\ l}$$

Movement along the z-axis: Movement along the z-axis measures the movement of the stylus along the z-axis in world coordinates as shown in Figure 2.2. In the game. Z-axis differs from the X and Y axis in the sense that participants need to move the painting ball in the XY plane to paint the bars but they do not need to move the stylus along the Z-axis to complete the task, except to position the ball at the beginning of the game and to return the stylus to the original position after a level is finished. This measurement tells how frequently the participant moved their stylus in the direction perpendicular to the screen, which is not required to finish the task, but may reflect the user's nonintentional operation and response to stimuli, especially touch sensations.

Similar to other measurement, movement along the z-axis is also normalized by the game play duration. In order to fully defined this measurement two more parameters are needed- direction of the movement and movement threshold. Players can move their painting ball in positive z-direction or negative z-direction. Moreover, the range of movement should also be defined. The interval defined as range of movement tells how far the ball has to be removed from the bars so that it is acceptable to count it as a *movement along the z-axis.* In this study, the range of movement lies between 0-1.5 units in negative z-direction (away from the screen) and 0-0.5 units in positive z-direction (towards the screen) where one unit in world coordinates is approximately 2.8mm. The resolution of measurement is 0.01 therefore, vibrations that produce movements smaller than 0.01 units are not registered by the system.

Gaze Sparsity: This measurement measures how densely or evenly, gaze points of participants are distributed on the screen. Due to the presence of special visual stimuli in the virtual environment, we expect participants with ASD and TD participants show different pattern in their gaze distribution. The gaze sparsity assigns a value between 1 and 10000 to a gaze distribution. A gaze distribution that is evenly distributed has higher gaze sparsity value than the gaze distribution where gaze points are concentrated in small areas.

The following example illustrates how gaze sparsity is calculated for any gaze distribution based

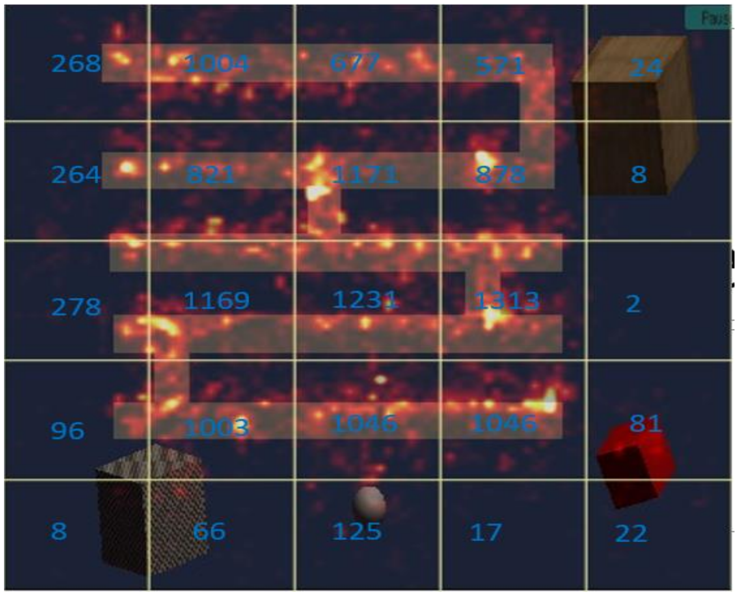

Figure 4.1 A heat map showing gaze points distribution

on the heat map. To create a heat map, we first construct a 2D histogram of the gaze points on the screen. Since, gaze points have coordinates in viewport coordinates all gaze points lies within the range (0,0) to (1,1). Therefore, by using 'n' number of bins for the 2D histogram we are essentially segmenting X axis and Y axis into 'n' intervals each extending 1/n units. Therefore, the screen is divided into n^2 square regions. The higher the number of gaze points that lies in a square the brighter the square appears. The brighter colored region shows areas where there is a large number of gaze points whereas, the darker regions are the areas with relatively less number of gaze points.

Figure 4.1 is a heat map generated using a participants' gaze data during an actual experiment session. For the purpose of clear illustration, we divide the heat map into 5×5 square regions. For the actual data analysis, we have used 100×100 squares regions, which gave us the most distinguished values between participants with ASD and TD participants (see section 5.4). As we increase the number of squares, we get better estimation of the sparsity based on the heat map.

To compare the sparsity (or density) of gaze point distribution, we first calculate the total number of gaze points collected in one level. Then, the number of gaze points inside each square was calculated. We sorted the squares according to the number of gaze points in each square. Starting from the square that has the maximum number of gaze points, we accumulated this maximum number with the number of gaze points in the square with the second highest number of gaze points. This accumulation continues with the following squares. For example, for the heat map shown above, we notice the maximum is 1312, and then next numbers are 1123, 1171, and so on. Therefore, the sequence of summation will be 1312+1231+1171+… We continued this summation until we reach a percentage of the total number of gaze points. In this thesis study, we chose the threshold as 80%. The total number of gaze points in the heat map is 13189 and 80% of which is 10551. Therefore, we keep adding until we exceed 10551, and then the least number of squares we needed to add to exceed 10551 will give the *gaze sparsity* of this game episode. In this case, the gaze points summation was in the sequence of: 1313 + 1231 + 1171 + 1169 + 1046 + 1046 + 1004 + 1003 + 878 + 821 = 10682, which was just greater than 10551. Therefore, at least 10 squares (sorted from the one containing the most gaze point to the next one with the second most points, etc.) were added get to reach the 80% threshold. Thus, the gaze sparsity was 10.

AASP scores: All participants filled an AASP questionnaire before playing the game. AASP data provided the fundamental sensory patterns of the participants measured by a standard psychological instrument. AASP questionnaire provides a score for each of the four sensory-processing-patterns. It was also possible to extract scores for each of the six senses (i.e., taste/smell processing, touch processing, visual processing, movement processing, activity level auditory processing) in AASP. In this thesis study, we frequently use scores in visual processing and touch processing categories to help us understand the participants' visual and touch sensory patterns, and link their response to visual and touch stimuli presented in the virtual environment. AASP scores also provided a psychological baseline for us to understand whether the four measurements (i.e. Performance, Gaze ratio, Gaze sparsity, Movement along the z-axis) obtained from the system aligned with standard psychological test results.

The experimental data was analyzed based on the measurements defined previously. In next section, we discuss statistical analysis on the defined measurements. In some cases, we observed significant differences between participants with ASD and TD participants. We also found statistically significant relations between psychological measurements and measurement collected by the VR system.

The statistical analyses used in the next section include: Independent t-test, paired t-test, Cohen's d effect size and Pearson's coefficient. In this thesis study, independent t-test is used to compare the results obtained from the two groups (adolescents with ASD and TD adolescents). Paired t-test is used to compare the difference in results within a group for different settings. The significance level for this study is $p < 0.05$. Effect size is calculated using Cohen's d formula. Effect size of d =.2 is considered small, d =.5 is considered medium and effect size larger than d = 0.8 is considered large [44]. Correlations between any two measurements is calculated using the Pearson's correlation coefficient.

5 Results

5.1 Performance

Table 5.1 Performance

ID	TD	ASD
1	112.36	106.34
2	125.65	121.65
3	94.86	137.57
4	68.52	162.93
5	90.36	92.03
6	117.86	79.4
7	112.52	156.61
8	90.72	70.15
9	118.58	106.58
10	109.48	78.90
11	77.34	57.62
12	90.11	109.52

The following table (Table 5.1) shows average performance of each participant. There is no significant difference in average performance between participants with ASD and TD participants. We also observed very small effect size as shown in Table 5.2. Therefore, performance alone was not sufficient to distinguish participants with ASD from TD participants.

5.1.1 Relation to other measurements

IQ: A strong positive correlation was observed between performance and IQ in participants with ASD (Pearson's coefficient $r = 0.833\ ; p = 0.002$). This correlation was interesting because the system itself was simple, and it was not designed to be dependent on IQ. Nevertheless, IQ of ASD participants seemed to determine their performance. Note that only a weak correlation existed between age and IQ of the participants

with ASD (r = -0.168; p = 0.642). This suggests that the relationship between IQ and performance was not influenced by age. However, this relation does not provide any direct information about sensory differences in participants' AASP scores.

Table 5.2 Mean and standard deviation of performance

	Mean	Standard Deviation
ASD	106.608	32.035
TD	100.698	17.135
p-value	0.594	
Effect size	0.230	

Table 5.3 IQ and performance in participants with ASD

Subject ID	1	2	3	4	5	6	7	8	9	10	11	12	r	*p*
IQ	117	133	126	--	--	114	129	89	124	99	59	116	0.833	0.002
Performance	106	121	137	162	92	79	156	70	106	78	57	109		

We observed a strong negative correlation between sensation avoiding score of touch processing category of participants with ASD and their performance (Pearson's coefficient $r = -0.642$ and $p = 0.002$). Meanwhile, we did not observe any strong or medium correlation between performance of TD participants and their AASP scores in any category (r =-0.0441-0.409; p = 0.891-0.186).

Table 5.4 Performance and touch processing sensation avoiding scores in participants with ASD

Subject ID	1	2	3	4	5	6	7	8	9	10	11	12	r	*p*
Performance	106	121	137	162	92	79	156	70	106	78	57	109	-0.642	0.024
Sensation Avoiding	10	12	8	5	12	9	4	8	10	10	11	10		

Table 5.5 Performance and sensation avoiding scores in participants with ASD

Subject ID	1	2	3	4	5	6	7	8	9	10	11	12	r	*p*
Performance	106	121	137	162	92	79	156	70	106	78	57	109	-0.728	0.007
Sensation Avoiding	40	42	38	31	44	42	22	44	43	39	48	51		

Table 5.6 Performance and sensory sensitivity scores in participants with ASD

Subject ID	1	2	3	4	5	6	7	8	9	10	11	12	r	*p*
Performance	106	121	137	162	92	79	156	70	106	78	57	109	-0.546	0.066
Sensory Sensitivity	28	42	46	38	30	62	42	25	32	36	24	45		

There was a strong negative correlation between performance and sensation avoiding score in participants with ASD (r =-0.728; p = 0.007).

There was also a moderate negative correlation between sensory sensitivity and performance in participants with ASD (r=-0.546; p = 0.066). We anticipated that there would be a moderate to strong correlation between touch processing scores and performance in participants with ASD.

This is because the task required participants to slide the painting ball against the bars that generated feelings of frictions. Hence, if touch sensory abnormalities are common in adolescents with ASD, we expected to find some relation between their performance and their touch processing score. Table 5.4 and Table 5.5 support our hypothesis. A strong correlation was observed between sensation avoiding score and performance in participants with ASD as shows in Table 5.5. This implies that for participants with ASD, the sensation avoiding behaviors beyond the touch modality might also have influenced their performance. The negative sign indicates that the stronger their sensation avoiding behavior was the more adversely their performance was affected. Sensory sensitivity behavior affected performance of participants with ASD in a similar way as shown in Table 5.6. The tendency to avoid sensation would grow stronger with higher sensory sensitivity score because they are able to sense small stimuli. This may explain the negative correlation between sensory sensitivity and performance in participants with ASD.

5.2 Gaze ratio

The following tables shows average gaze ratio of each participant.

Gaze data for participants' TD-01 and ASD-03 were not available The eye tracker was unable to track their gaze due to frequent head and body movements. The standard t-test analysis between gaze ratio of two groups does not show any significant difference (p=0.320*)*. Although the effect size is moderate distractions (d=0.455) Relation to other measurements AASP scores: There is a moderate correlation between sensation avoiding score of visual processing category and gaze ratio in TD participants (Pearson's coefficient $r = 0.483\ and\ p = 0.131$). Whereas, no such correlation was obtained for participants with ASD and their sensation avoiding score in visual processing category (r=0.017-0.401; p=0.617-0.210). Although the correlation was not strong, sensation avoiding behavior seemed to be a dominant behavior than other behaviors during the experiment. There is also a moderate negative correlation between low registration score of visual processing category and gaze ratio in participants with ASD as shown in Table 5.10. This correlation was also observed in the previous study with half the sample size[45]. Since, low registration. behavior entails low sensitivity towards stimuli it is reasonable to assume that participants with high low registration score will be less affected by the distracting objects.

Table 5.7 Gaze ratio

ID	TD	ASD
1	--	0.063
2	0.070	0.070
3	0.0592	--
4	0.078	0.092
5	0.047	0.107
6	0.072	0.068
7	0.096	0.086
8	0.057	0.070
9	0.054	0.054
10	0.086	0.083
11	0.069	0.097
12	0.087	0.060

Table 5.8 Mean and standard deviation of gaze ratio

	Mean	Standard Deviation
TD	0.0708	0.0146
ASD	0.0778	0.0161
p-value	0.320	
Effect Size	0.455	

Table 5.9 Gaze ratio and visual processing sensation avoiding scores in TD participants

Subject ID	1	2	3	4	5	6	7	8	9	10	11	12	r	*p*
Gaze Ratio	--	0.070	0.059	0.078	0.049	0.072	0.096	0.057	0.054	0.086	0.069	0.087	0.483	0.131
Sensation Avoiding	10	11	8	8	6	6	9	9	7	9	6	11		

Table 5.10 Gaze ratio and visual processing low registration scores in participants with ASD

Subject ID	1	2	3	4	5	6	7	8	9	10	11	12	r	*p*
Gaze Ratio	0.063	0.070	--	0.092	0.107	0.068	0.086	0.070	0.054	0.083	0.097	0.060	-0.410	0.201
Low Registration	5	2	4	--	2	6	2	7	4	7	5	8		

Table 5.11 Gaze ratio and sensation seeking scores in participants with ASD

Subject ID	1	2	3	4	5	6	7	8	9	10	11	12	*r*	*p*
Gaze Ratio	0.063	0.070	--	0.092	0.107	0.068	0.086	0.070	0.054	0.083	0.097	0.060	0.571	0.066
Sensation Seeking	47	27	42	46	46	41	50	46	34	56	52	38		

Table 5.11 shows a moderate positive correlation between sensation seeking and gaze ratio in participants with ASD ($r = 0.571\ and\ p = 0.066$).sensation seeking is associated with the tendency to seek and enjoy stimuli. Therefore, the fact that it is positively correlated with the tendency to spend more time looking at the distracting object is reasonable.

5.3 Movement along the z-axis

There is a big difference in extent to which participants with ASD and TD participants moved the ball along z-axis as shown in the following sections.

5.3.1 In negative z-direction

Table 5.12 Movement along the z-axis in negative z-direction

ID	ASD	TD
1	5.306	5.102
2	4.816	6.174
3	4.986	4.842
4	4.442	8.811
5	4.576	5.274
6	4.595	6.263
7	6.247	7.659
8	5.592	6.469
9	4.908	6.444
10	7.024	6.572
11	5.448	13.77
12	4.294	5.375

Table 5.12 shows the difference in movement along the negative z-axis between participants with ASD and TD participants. The value in each cell in Table 5.12 is the number of times the corresponding participant moved their painting ball away from the bars and within the range of movement (see section 4) divided by the total duration of the level. There was a significant difference between the two groups in this measure ($p = 0.030$). Effect size was also large at 0.984. Hence, TD participants moved their stylus away from the painting plane significantly more than participants with ASD. Figure 5.1 shows the possibility of distinguishing participants with ASD and TD participants on the basis of their average score for 'movement along the negative z-axis'. When we use Spectral clustering method to form two clusters for the

participants, using movement along the negative z-axis as one dimensional feature, we obtain the result as shown in Table 5.14.

Table 5.13 Mean and standard deviation (negative z direction)

	Mean	Standard Deviation	p-value	Effect size
ASD	5.186	0.767	0.030	0.984
TD	6.891	2.332		

Spectral clustering treats data as a graph, called similarity graph, where each data point represents a vertex in the graph [46]. Two vertex are connected by an edge if they are similar based on the defined metric. Finally, data points are clustered based on the similarity between the vertices. Each cluster is a group of vertices which are highly connected internally and there are only few edges connecting two different clusters. In our study, the similarity graph is constructed using k-nearest neighbor method. A vertex is connected to another vertex if it is one of the k nearest neighbor of the vertex (k=2 is used for this analysis. Based on the similarity graph we can construct two matrices called Adjacency matrix (A)and Degree matrix (D). Each entry of the adjacency matrix a_{ij} represents the similarity between vertices i and j The degree matrix D is a diagonal matrix which diagonal entry d_{ii} is the number of edges connected to the vertex i. The graph Laplacian (L) is given by $L = D - A$.

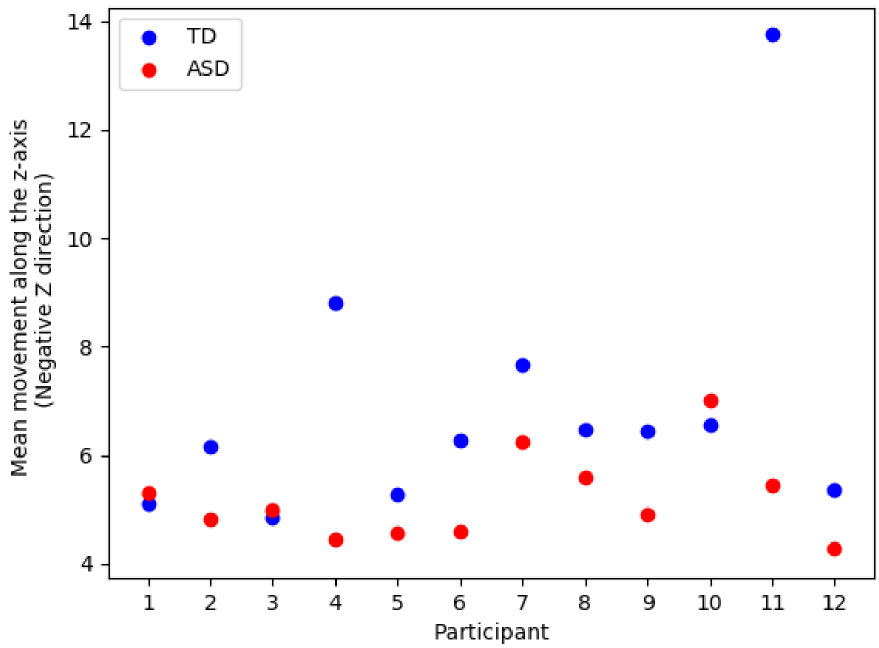

Figure 5.1 Movement along the z-axis in negative z direction

Table 5.14 Confusion matrix (negative z direction)

		Predicted	
		ASD	TD
Actual	ASD	8	4
	TD	2	10

Finally, the eigenvalues and the corresponding eigenvectors of the graph Laplacian tell to which clusters the vertices belong to.

Here, we have assumed that the cluster where majority of data points belong to participants with ASD is the ASD cluster, and the cluster where the majority of data points belong to TD participants is the TD cluster. The classification gives precision of 0.800 and recall of 0.667. Therefore, the F1 score = 0.727

Figure 5.1 suggests that participant TD-11's measurement may be an outlier of the group. Hence, there is a possibility that removing the outlier may give a more accurate result. Table 5.15 shows the difference in score becomes more significant after removal of the outlier. P-value increased to 0.016 from 0.03 and effect size also increased to 1.141 from 0.984.

Table 5.15 Mean and standard deviation after removing the outlier (negative z direction)

	Mean	Standard Deviation	p-value	Effect size
ASD	5.186	0.767	0.0163	1.141
TD	6.271	1.118		

5.3.2 In positive z-direction

Table 5.16 Movement along the z axis in positive z direction

ID	ASD	TD
1	4.079	1.277
2	3.593	4.837
3	4.055	6.417
4	4.897	5.968
5	3.467	4.997
6	3.038	6.354
7	3.768	6.742
8	4.428	5.138
9	5.674	3.965
10	3.07	3.535
11	5.443	5.145
12	3.313	4.108

We obtained similar results in the analysis of movement along the z-axis in positive z-direction. Similar to the negative z-direction case, TD participants had more movement along the z-axis than participants with ASD. The effect size was also medium with the value of 0.678. we observe the similar phenomenon in Figure 5.2. There is a clear division between TD data points and ASD data points. Passing the data through the Spectral clustering algorithm, again, gives result as shown in Table 5.18.

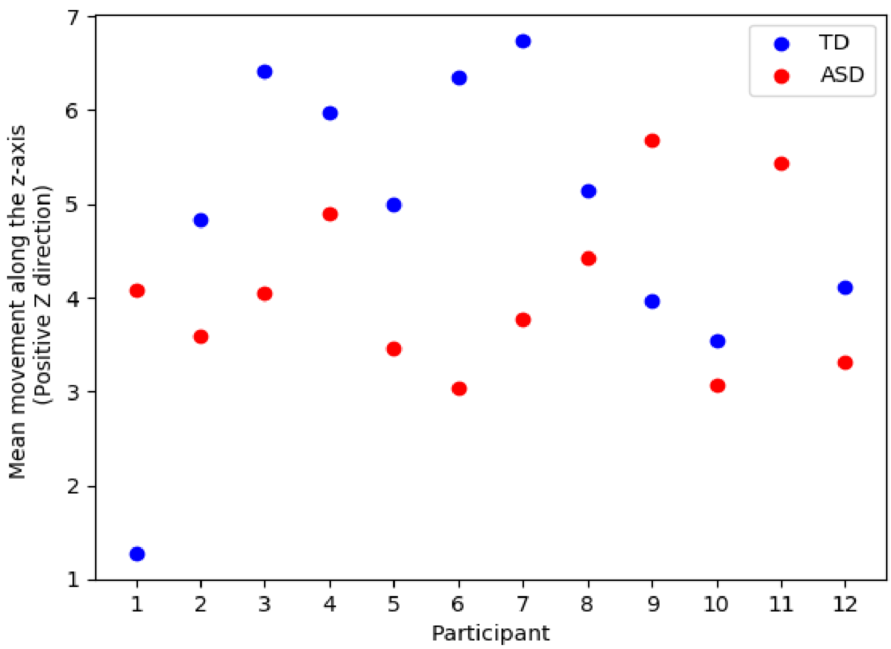

Figure 5.2 Movement along the z-axis in positive z direction

Therefore, the accuracy of the clustering method is 75% with precision of 0.75 and recall of 0.75. The F1 score = 0.75 It is evident from Figure 5.2 that TD-01's data lies outside the aggregate range of the data points and can be treated as an outlier. Removing TD-01 results in increase of the statistical measures of the differences between the two groups.

Table 5.17 Mean and standard deviation in positive z direction

	Mean	Standard Deviation	p-value	Effect size
ASD	4.068	0.846	0.127	0.674
TD	4.873	1.459		

Table 5.18 Confusion matrix (positive z direction)

		Predicted	
		ASD	TD
Actual	ASD	9	3
	TD	3	9

Table 5.19 Mean and standard deviation after removing the outlier TD-01

	Mean	Standard Deviation	p-value	Effect size
ASD	4.068	0.846	0.011	1.213
TD	5.200	1.020		

Therefore, removing the outlier makes the difference more statistically significant. p-value improved from 0.127 to 0.011 and effect size almost doubled from 0.674 (previous value) to 1.213 (current value).

5.3.3 Relation to other measurements

AASP score: We observe a strong positive correlation between movement along the z-axis in negative z-direction and sensation seeking score in participants with ASD ($r = 0.646$ and $p = 0.023$). The haptic robot provides touch stimuli in terms of force feedback and vibration. Therefore, participants with larger sensation seeking score might have been trying to stimulate themselves with the touch stimuli by moving their stylus more frequently than others.

5.4 Gaze Sparsity

Table 5.20 Gaze sparsity

ID	ASD	TD
1	209.33	--
2	320.33	386.75
3	--	--
4	350.83	560.08
5	--	176.83
6	437.75	639.83
7	315.83	600.75
8	--	551.91
9	278.66	--
10	--	--
11	415.16	586.25
12	270.58	314.58

This measure showed that the gaze distributions in participants with ASD and TD participants were clearly different. The gaze pattern was affected by the position of the distracting objects and the structure of the bars. Therefore, in order to do statistical analyses, it is sensible to compare the gaze data of participants on the same levels. First, we took the gaze sparsity data of the participants who did not have any missing data across all 12 level to perform statistical analyses on the data. The data clearly shows the big difference between gaze sparsity of two groups. On average, TD participants has their gaze more evenly distributed on the screen than the participants with ASD. This result tells that the participants with ASD focused their gaze at some specific points whereas TD participants were scanning the screen more often. Figure 5.3

clearly shows the distinction in gaze sparsity between the two groups. 5 out of 8 TD participants has gaze sparsity score higher than any participant with ASD. The graph shows the possibility of two separate clusters representing data TD participants and participants with ASD. The classifier correctly grouped all 8 TD participants in one group however, it clustered 3 participants with ASD in TD group. The accuracy of the classifier is 81.25%, the precision of the classifier is 1.00, and the recall is 0.625. Therefore, the F1 score = 0.769.

Table 5.21 Mean and standard deviation of gaze sparsity

	Mean	Standard Deviation	p-value	Effect size
ASD	324.81	70.80	0.032	1.267
TD	477.12	154.47		

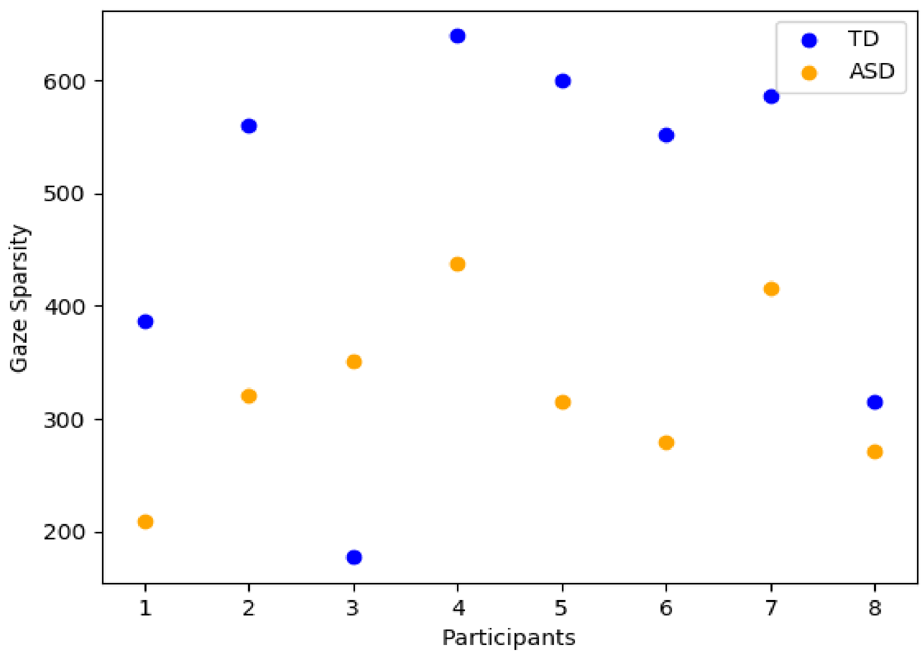

Figure 5.3 Average gaze sparsity

Table 5.22 Confusion matrix for the clustering based on gaze sparsity

		Predicted	
		ASD	TD
Actual	ASD	5	3
	TD	0	8

Instead of using the average of gaze sparsity of each participant as a feature for the clustering if we use sparsity of all 12 levels as 12 dimensional feature we obtain the same result. The classifier clusters all TD participants in one cluster, however, it misclassifies 3 participants with ASD as TD participants. If the restriction of having the gaze data of only those participants who have played all 12 levels is removed, we get the result as shown in Table 5.23.

Table 5.23 Gaze sparsity (11 participants)

	TD	ASD
1	--	209.33
2	386.75	320.33
3	355.45	--
4	560.08	350.83
5	176.83	285.36
6	639.83	437.75
7	600.75	315.83
8	551.91	551.36
9	298.36	278.66
10	396.81	383.10
11	596.25	415.16
12	314.58	270.58

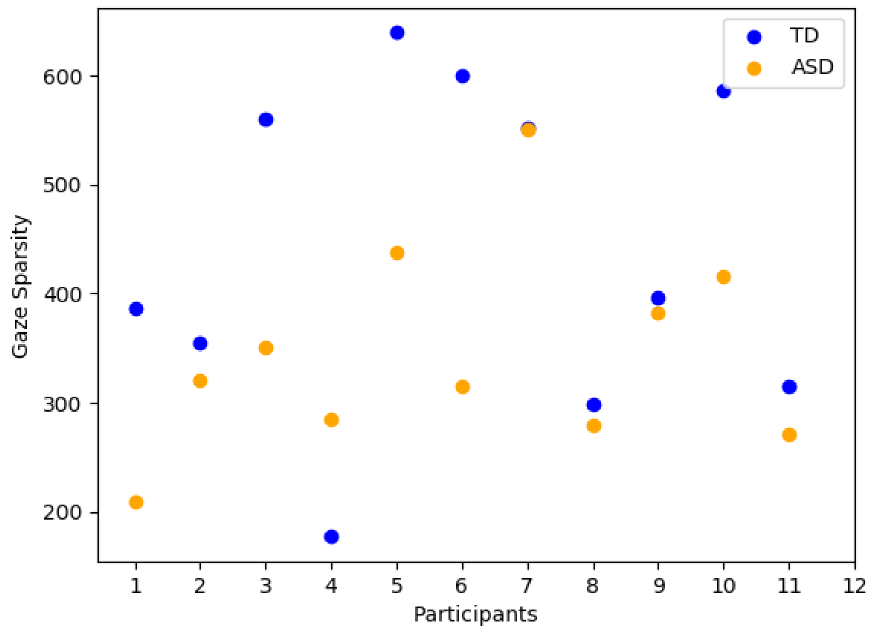

Figure 5.4 Gaze sparsity (11 participants)

Table 5.24 Mean and standard deviation (11 participants)

	Mean	Standard Deviation	p-value	Effect size
ASD	347.12	144.90	0.093	0.788
TD	442.49	90.90		

Although p-value increased to 0.0931 and the difference does not remain as statistically significant as the previous result, the difference is still noticeable.

5.5 3D and 2D Scenarios

Table 5.25 shows the performance of participants in 2D levels and 3D levels separately. The Effect size and p-value columns shows the result of comparing the performance of participants with ASD and TD participants in 2D levels, in 3D levels and across all levels.

Table 5.25 Performance in 2D and 3D scenarios

	Mean		Std		Effect size	p-values
	TD	ASD	TD	ASD	TD vs ASD	TD vs ASD
2D	96.092	108.152	16.865	34.092	0.448	0.304
3D	106.614	105.689	20.080	30.205	-0.084	0.933
All Levels	100.698	106.608	17.135	32.035	0.230	0.594

Table 5.26 3D vs 2D performance p-values

	TD	ASD
p-value 2D vs 3D	0.031	0.445

The virtual environment has 6 scenes which are 2 dimensional in nature and other 6 scenes which are 3D in nature. Data shows (Table 5.25) that this additional depth information has a significant impact on the performance of TD participants. Here, we observed that performance of participants with ASD stayed almost the same when moving from 2D scenes to 3D scenes whereas, performance of TD participants increased sharply. Paired t-test analysis between the performance in 2D and 3D scenarios showed this fact clearly (see Table 5.26). For TD participants the p-value was significant whereas the for participants with ASD the p-value remained insignificant. Table 5.27 and Table 5.28 shows the result of conducting similar analysis on gaze ratio of participants. The result shows that both participants with ASD and TD participants were less distracted in 3D scenarios than in 2D scenarios. This difference was significant in participants with ASD However, since they played levels with 2D scenarios before

the 3D scenarios, it can be argued that they became desensitized to distracting objects as they progressed along the game which resulted in lower gaze ratios in the later levels

Table 5.27 Gaze ratio in 3D and 2D scenes

	Mean		Std		Effect size	p-value
	TD	ASD	TD	ASD	TD vs ASD	TD vs ASD
2D	0.075	0.083	0.017	0.015	0.525	0.253
3D	0.066	0.071	0.015	0.019	0.299	0.510
All Levels	0.070	0.077	0.014	0.016	0.455	0.323

Table 5.28 3D vs 2D gaze ratio p-values

	TD	ASD
p-value 2D vs 3D	0.093	0.015

5.6 AASP Scores

Two tailed t-test on AASP scores for participants with ASD and TD participants showed that there was a significant difference between them in Sensation avoiding behavior in touch processing category.

Table 5.29 TD vs ASD touch processing scores

	p-value
Low Registration	0.935
Sensation Seeking	0.946
Sensory Sensitivity	0.848
Sensation Avoiding	0.009

Table 5.30 TD vs ASD visual processing scores

	p-value
Low Registration	0.539
Sensation Seeking	0.484
Sensory Sensitivity	0.768
Sensation Avoiding	0.265

Table 5.31 TD vs ASD total scores

	p-value
Low Registration	0.611
Sensation Seeking	0.962
Sensory Sensitivity	1.0
Sensation Avoiding	0.347

There is no significant difference between scores of participants with ASD and that of TD participants in any other categories in AASP. Results implied that the impact of Sensation avoiding could have strongly impacted the performance of the participants with ASD. We also observed higher movement along z-axis measurement and sparsity in TD participants than participants with ASD. It also important to notice that there was a difference in sensation avoiding score between the two groups. Sensation avoiding is associated with a tendency to avoid stimuli or sensations and that can also explain the small movement along z-axis value and gaze sparsity value in participants with ASD. As a way to minimize or avoid unfamiliar stimuli, participants with ASD could have preferred to focus on some specific spots or move their stylus in a fixed manner.

6 Discussion and Conclusion

In this thesis study, we developed a VR system to assess sensory abnormalities in adolescents with ASD. The system was able to demonstrate two things: 1) It was able to find differences between adolescents with ASD and TD adolescents based on their interaction with the system. 2) The measurements collected from the system have some alignment with standard traditional sensory profile assessment scores (i.e., AASP), while can disclose participants' subtle responses to different stimuli in a finer resolution.

. We observed a strong correlation between performance and IQ of participants with ASD ($r = 0.8335$; $p = 0.002$). Interestingly, the game did not involve any task that required mental calculation or dexterity. Some studies have suggested that sensory abnormality is affected by age and IQ [15], [16]. We did not observe any correlation between performance and age of the participants. Therefore, it may indicate that sensory abnormalities were affected by IQ and that eventually affected performance of the participants This leads to a strong indirect relation between sensory abnormalities and performance. Unfortunately, because of lack of IQ information for TD participants, we are unable to compare this result with TD participants

Similar to studies [13], [39] we observed differences in sensation avoiding scores between participants with ASD and TD participants. Participants with ASD exhibited higher sensation avoiding score than TD participants. Especially participants with ASD differed significantly from TD participants in sensation avoiding score in touch processing category ($p = 0.009$). Since, the participants constantly received touch stimuli when playing the game, we expected to find a relation between touch sensory abnormalities and the performance. The data supported our assumption and showed a strong correlation between sensation avoiding score and performance in adolescent with ASD. There were strong negative correlations between performance and both total sensation avoiding score (r =-0.728; p = 0.007) and sensation avoiding score in touch processing category (r =-0.642; p = 0.020). Furthermore, we observed moderate negative correlation between sensory sensitivity and performance (r =-0.546; p = 0.066) in participants with ASD. These correlations look natural given that participants with ASD had their performance negatively affected by their sensation avoiding score and sensory sensitivity entails heightened sensitivity towards sensory stimuli. No such correlations were obtained for TD participants. This suggests that the system can find sensory differences associated with sensation avoidance behavior based on the users' performance.

Although we did not observe any differences in direct measurements i.e. gaze ratio and performance-there were significant differences in other subtle measurements – gaze sparsity, movement along the z-axis and differences between 3D and 2D scenarios. TD participants scored significantly higher in both gaze sparsity and movement along the z-axis measurements. The differences were strong enough that it was possible to cluster most TD participants and participants with ASD into two distinct groups. This result also implies that TD participants were more actively seeking visual and touch sensation. It is interesting to note that study [13], with a much larger sample size than that of our study, reported lower sensation seeking score in adolescents with ASD than the control group. Although, there were no significant difference in sensation seeking score between participants with ASD and TD participants, we did observe a moderate positive correlation (r = 0.646; p = 0.023) between movement along the z-axis and sensation seeking score in participants with ASD. Therefore, it could be the case that those two measurements disclosed lower sensation seeking behavior in participants in ASD compared to TD participants, despite having similar sensation seeking scores in AASP. In this case, AASP was not able to capture the difference in sensation seeking behavior between the two groups.

Nevertheless, the system was able to reveal these subtle differences which could be the result of sensory abnormalities not apparent in AASP scores. This is also supported by the fact that participants with ASD had higher sensation avoiding score, which means they would try to avoid or reduce sensory stimuli. Hence, fixating their gaze on a fixed spot and firmly holding the stylus could be a way to minimize the extent of interaction they have with the virtual environment to reduce sensory stimuli.

Participants with ASD and TD participants demonstrated different responses to presence or absence of depth information in the scene. By comparing the performance of each group in 3D and 2D levels, we were able to see how depth information affects their behavior. The difference in performance of participants with ASD and TD participants is relatively larger in 2D levels ($p = 0.304$) than in 3D levels ($p = 0.933$) but not significant. However, the difference in improvement in performance between the two groups, moving from 2D to 3D levels, was noticeable. TD participants had significantly better performance in 3D levels than in 2D levels whereas there was not a significant difference in participants with ASD. The result showed that TD participants took advantage of depth information more than the participants with ASD. One reason for this behavior might also be linked to the sensation avoiding tendency. Participants with ASD might be filtering out additional visual information like depth information which was not directly relevant to finishing the task. However, how this results relate to sensory abnormality is not clear.

Hence, the system was able to show some differences between adolescent with ASD and TD adolescents based on the defined measurements. However, there are several limitations to this study and several ways to further improve the system. Small sample size is one of the limitations of this thesis study as it is difficult to draw a statistically significant conclusion from a small sample. It is also impossible to fully shield participants from other sources of stimuli in the environment. Therefore, despite our best attempt to minimize external distractions (e.g no decoration in the room) it is not possible for us to know to what extent the environment affected our results. Furthermore, we only considered two types of sensations i.e. touch and visual for this study. We can improve the system by incorporating other types of sensations such as auditory, olfactory, etc. This would allow us to find sensory abnormalities in other sensory modalities and better map sensory abnormalities to underlying ASD. The system did not have a feedback mechanism which is another limitation. Without the feedback, the system was not able to change the virtual environment based on the response of the user. As a consequence, we cannot capture sensory abnormalities of the participants that is not triggered by the fixed configuration of the virtual environment. This reduces the range of sensory abnormalities that can be assessed by the system. Moreover, it is clear that efficacy of the system to capture the differences between the two groups depends on the defined measurements. However, the choice of measurement is essentially arbitrary. It is possible that some other measurements would have provided more accurate and decisive result than the measurements we used. Therefore, it is possible that a new measurement or data analysis technique exists that can disclose important sensory difference based on the raw data collected from the system.

Also, with appropriate measurements, we may be able to develop a statistical model which can classify participants with high accuracy. Therefore, the current study leaves plenty of room for improvements, and to make the system more comprehensive and accurate in the future.

7 References

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