Understanding the Psycho-Physiological Implications of Interaction With a Virtual Reality-Based System in Adolescents With Autism: A Feasibility Study

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***Abstract*—Individuals with Autism are characterized by deficits in socialization and communication. In recent years several assistive technologies, e.g., Virtual Reality (VR), have been investigated to address the socialization deficits in these individuals. Presently available VR-based systems address various aspects of social communication in an isolated manner and without monitoring one's affective state such as, anxiety. However, in conventional observation-based therapy, a therapist adjusts the intervention paradigm by monitoring one's anxiety level. But, often these individuals have an inherent inability to explicitly express their anxiety thereby inducing limitations on conventional techniques. Physiological signals being continuously available and not directly impacted by these communication difficulties can be alternatively used as markers of one's anxiety level. In our research we aim at designing a Virtual-reality bAsed Social-communication Task (VAST) system that can address the various aspects of social communication, e.g., social context, subtle social cues, emotional expression, etc., in a cumulative and structured way. In addition, we augment this with a capability to use one's physiological signals as markers of one's anxiety level. In our preliminary feasibility study we investigate the potential of VAST to cause variations in one's performance and anxiety level that can be mapped from one's physiological indices.**

***Index Terms*—Anxiety, autism, physiology, virtual reality (VR).**

I. Introduction

AUTISM spectrum disorder (ASD) is a neurodevelopmental disorder with prevalence rate of 1 in 150 adolescents in India [1]. Autism is characterized by deficits in two core areas, namely: communication and social deficits, and fixed or repetitive behaviors [2]. Autism remains as a behaviorally defined syndrome with no universally accepted treatment or cure. But there is an increasing consensus that intensive behavioral and educational programs can strengthen the social communication skills and significantly improve long term outcomes for these individuals [3].

The limitations on the conventional observation-based intervention techniques for individuals with ASD include limited trained professionals and enormous cost of one-to-one intervention sessions [4]. Many studies have investigated applications of technology as assistive therapeutic tools for adolescents with autism, namely, computer technology [5], Virtual Reality (VR) [6], and robotic systems [7]. We chose VR because it offers malleability, controllability, modifiable sensory stimulation, an individualized approach, safety and potential reduction of problematic aspects of human interaction particularly during initial skill training [4], [8]. It provides a simplified but explorative training environment with no complex direct human-to-human interaction. VR technology may offer efficient generalization of skills from a VR-based environment to the real world, since it mimics real environments in terms of imagery and contexts [4], [9]. The VR-based environment here refers to the visualization developed to replicate a social communication training context. Thus, VR is a suitable medium for adolescents with autism. With advances in computing technology, VR-based systems are now readily available in a cost-effective manner. These systems can also serve as a complimentary tool in the hands of the interventionists.

Literature review shows pioneering work being carried out on the applicability of the VR-based platform for addressing daily living skills for ASD adolescents [4], [8]. Studies have shown the use of the VR environment, which takes into account different aspects of social communication, such as social context, subtle social cues, social interaction [6], facial emotional expression [7], etc., in an isolated way. However, there is no VR-based research study in India, to our knowledge, that has explored the different aspects of social communication, such as social context, subtle social cues, emotional expression, etc., having a cumulative effect on adolescents with ASD. In our research, we have tried to expose our participants to different aspects of social communication in a cumulative and structured manner. In addition, given that research in this field in Indian context is rare, we have considered the subtle aspects e.g., skin complexion, language, social communication norms covering aspects of social distance, conversation initiation, etc., relevant to Indian cultural context while designing the system. Also in social communication, apart from adhering to social norms, it is also essential that one adequately performs in a social task. In fact, in conventional intervention techniques, the therapist/interventionist not only offers a proper intervention environment, but also monitors the participant's performance in the task to adapt her intervention strategy. In our research, we have also taken the participant's performance in the VR-based social communi-

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cation task into consideration before offering tasks of varying challenges to the participant.

In conventional intervention sessions, the therapist monitors a participant's performance and maps that to his affective state, such as anxiety for deciding on the floor-time-therapy [10]. The therapist's expert eyes look for the participant's subtle affective cues observed from facial expression, vocal intonation, gestures, postures, etc. However, adolescents with autism often possess deficits in explicit expression of their affective state which often pose limitations on traditional observational and conventional techniques. Additionally, given the scarcity of trained professional resources, researchers have been studying the potential of other modalities, such as physiological signals which can be mapped to one's affective state. Studies show that physiological signals can be evoked by different amounts in the presence of virtual environments [11], [12] and transition from one affective state to another is accompanied by dynamic shifts in indicators of autonomic nervous system activation [13]. In addition, physiological signals being continuously available and not directly impacted by communication deficits may offer an avenue for recognizing one's affective state, which is less obvious for humans but more suitable for computers.

In this research, we aim at designing a Virtual-reality bAsed Social-communication Task system (VAST) addressing different aspects of social communication and trying to study its potential to elicit variations in one's physiological indices and performance score. The preliminary results of our feasibility study indicate a possibility of mapping one's physiological indices to his anxiety while interacting with VR-based social situations offering varying challenges to the participant. Here, we chose anxiety as the target affective state because of two reasons. First, anxiety plays an important role in human computer interaction [10] that can be related to performance, challenge, and the ability of the user [13]. Second, anxiety is a common concern in clinical samples for adolescents with autism [10] due to socialization deficits [14] which works adversely in an educational setting. In our present research, we exposed our participants to real-life social communication scenarios through VR-based tasks which might provoke anxiety among our participants due to their socialization deficits, thereby, adversely affecting their learning and performance. Thus it is essential to have an intelligent adaptive system that monitors and adjusts itself based on one's predicted anxiety level while participating in social communication tasks. As a step towards such a system, it is essential to realize the potential of a VR-based social communication system to predict one's anxiety level while interacting with a social situation. Here we are trying to understand the possibility of using one's physiological indices as markers of one's anxiety level. Several researchers in the field of human computer interaction have investigated the efficacy of physiology-based affect recognition systems for typical adults and individuals with ASD. For example, recently Kushki *et al.* in their non-VR-based research study involving both typical adults and individuals with ASD have shown that there occurs variations in one's physiology e.g., skin temperature, cardiac activity and perspiration [14] with one's anxiety level. They have mentioned that physiological response to anxiety is managed by a large network of neural structures in the central, peripheral and endocrine systems. The autonomic branch of peripheral nervous system is activated during anxiety to mobilize appropriate behavioral responses to stressful stimuli [14]. Specifically, activation of the sympathetic system during stress generally increases heart rate and eccrine sweat gland activity and decreases skin temperature [14]. However, such pioneering work did not consider the psycho-physiological implications on individuals when exposed to VR-based tasks offering social communication challenges to the participants.

The research study presented in this paper aims at designing a VAST system that: 1) addresses some of the different aspects of social communication, such as understanding social context, subtle social cues, e.g., gestures, facial expressions, etc.; 2) has potential to cause variations in one's physiological indices and performance while interacting with VR-based social communication task of varying challenges; and finally 3) can help us study the potential of mapping physiological indices to one's anxiety. Though our VAST system was not designed as an intervention platform, the preliminary feasibility study was designed as a proof-of-concept application. VAST was designed to address different aspects of social communication and was capable of monitoring one's physiological indices and measuring one's performance during a communication task. Subsequently, based on the performance measure, VAST switched tasks of varying difficulty along with physiological data acquisition for offline analysis. The remainder of the paper is organized as follows. In Section II we present the system design. Section III discusses the method used for the study, while Section IV presents the results obtained from the usability study. Section V summarizes the contribution of the present study and scope for future research.

II. System Design

The VAST system comprises three subsystems: 1) VR-based task presentation module; 2) task switching rationale; and 3) physiological data acquisition module.

A. VR-Based Task Presentation Module

In our study we chose desktop (standard Lenovo computer with 17″ monitor) VR due to its advantages over head-mounted VR in terms of affordability, accessibility and also because it is less prone to causing cyber sickness [4]. In the VR-based task presentation module, a humanoid character (avatar) narrated social stories while moving dynamically in a context-relevant virtual environment, demonstrated gestures, and shared his experience with the user. For this we designed avatars with programmed animations, e.g., gesturing, walking, speaking using VR modeling techniques (Section II-A1). We designed a social interaction platform using the VR visualization technique of mounting context-relevant scenes on a VR world (Section II-A3). We used menu-driven communication modules (Section II-A4) for avatar-participant interaction. The task presentation module is comprised of design and selection of: 1) avatars; 2) social stories; 3) virtual environments; and 4) participant's response interface.

The VR platform was designed using Vizard software from Worldviz, Inc. The software comes with limited resources such as avatars, virtual objects and scenes. So we designed avatars and virtual scenes to create different sets of social communication environments for our study.

1) Design and Selection of Avatar: The avatar heads were chosen from a database given by Virtual Human Interaction Lab at Stanford University, which were modeled from 2-D photographs of front and side faces of teenagers and converted to Vizard compatible 3-D heads by 3DMeNow software. This software (biovirtual.com) allows creation of interactive, photo-realistic humanoid avatars in realistic social scenarios. The complexion, hair, and eyebrow color of avatars were modified using Vizard-compatible GNU Image Manipulation Program (GIMP) software to render an Indian look. The avatar faces were programmed to display different emotions (morphs) using PeopleMaker software. A survey on these designed faces was conducted among 14 undergraduate students (Mean age: 21.4 yrs; Std. Dev: 3.6 yrs) to ensure that the avatar's facial emotional expression was interpreted by the viewers as was intended by the designer and also looked Indian. A total of 24 heads comprised of four male (M1–M4) and four female (F1–F4) heads displaying three emotions, e.g., happy, angry and neutral were designed for this survey. These heads were validated for different emotions based on the participant's response to questions asked on emotion, valence and arousal [15]. Question 1 (Q1) was aimed to measure participant's perception regarding the avatar's emotion with two options e.g., "specific emotion" and "no emotion/neutral". Questions 2 and 3 (Q2 and Q3, respectively) were used to measure the participant's elicited reaction from viewing the avatar's emotion which was marked on a 5-point scale $[-2, 2]$. The elicited emotions were rated based on the participants' response on a valence-arousal scale for Q2 and Q3. The selection of avatar was based on the overall rating for all three questions. Q2 gave valence mean $(\mathrm{V_{mean}})$ and Q3 gave arousal mean $(\mathrm{A_{mean}})$. Fig. 1 shows our approximated model of emotion used for this study. This model was selected since happy and angry are distinctly on opposite sides on the valence scale (normalized), e.g., positive $(+1)$ and negative (-1) valence. Arousal scale measured the degree of positivity or negativity of emotion. The zero value was assigned for neutral emotion for both valence and arousal. We calculated normalized Euclidean distance $(\mathrm{E_{norm}})$ for the designed avatar faces on a [0-1] scale using (1). The centroid $(\mathrm{C_V}, \mathrm{C_A})$ chosen for calculating $\mathrm{E_{norm}}$ for neutral faces was (0, 0). We choose two centroids, namely, $(1, 1)$ and $(1, -1)$ for happy and $(-1, 1)$ and $-1, -1)$ for angry faces. Using (2) we combined these for an overall rating $(\mathrm{R_i})$ of avatar heads giving more weightage on valence and arousal ratings which ensure reliable assessment of one's emotional states [15]

$$\mathrm{E_{norm}} = \frac{\sqrt{(\mathrm{V_{mean}} - \mathrm{C_V})^2 + (\mathrm{A_{mean}} - \mathrm{C_A})^2}}{2\sqrt{2}} \tag{1}$$

$$\mathrm{R_i} = 0.8\mathrm{E_{norm}} + 0.2\mathrm{Q_1}. \tag{2}$$

The selection of avatar was based on $\mathrm{R_i}$ computed for each avatar for each of the three emotions (Table I). Based on $\mathrm{R_i}$, three male (M1, M2, and M3) and three female (F1, F2, and F4) avatar faces were selected. Faces M4 and F3 were not considered as they had $\mathrm{R_i}$ values outside ± 1 std. dev. of their mean value (Tables I and II). The six selected avatars (three each for male and female) were used for our task presentation. Each avatar could display emotional expressions, use bone-kinematics for gestures and also move dynamically in the 3-D VR world by using the built-in "walkTo" function.

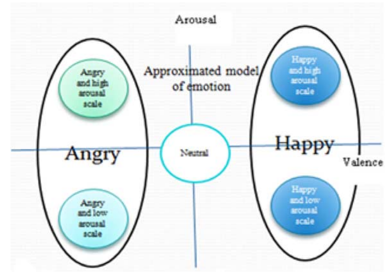

Fig. 1. Approximated emotion model.

TABLE I
VALUE $\mathrm{R_i}$ FOR AVATAR FACES

Avatar	Angry	Neutral	Happy
M1	0.274	0.155	0.067
M2	0.286	0.248	0.054
M3	0.259	0.320	0.135
M4	0.155	0.092	0.466
F1	0.290	0.230	0.149
F2	0.263	0.149	0.061
F3	0.141	0.346	0.279
F4	0.292	0.283	0.135

TABLE II
RANGE OF R_i FOR AVATAR FACES

Emotion	$\mathrm{R_i}$(mean $\pm$ std)
Angry	(0.25 $\pm$ 0.06)
Neutral	0.23 $\pm$ 0.09)
Happy	(0.17 $\pm$ 0.14

2) Selection of Stories: Social stories are individualized short stories that describe a social context by breaking down a challenging social situation into easily understandable ones. Social stories are effective in teaching social communication skills to children with ASD [16]. In our present study, we selected 24 social stories (following the guidelines in [16]) categorized as a memorable day in life, favorite sport, film, best friend, travel with family and field trip, etc., that are relevant for these adolescents. We chose these social stories to expose the adolescents with ASD to different social situations. These stories were recorded with audacity software in regional language (Hindi) in teenager's voice for our Indian participants. Care was taken to record the stories in monotone so that the participants did not receive any cues on the avatars' emotions from the vocal tone, except from the avatars' facial emotional expression. We used the built-in "speak" function for our avatars to speak these stories lip-synched with the recorded audio files.

3) Design of Virtual Environments: In our study, we designed virtual environments to display three context-relevant backgrounds for each story being narrated by the avatar. For the VR visualization to create social communication environments we created a database of 72 context-relevant photographs depicting social situations. These social situation-based backgrounds were mounted on a 3-D VR world to create social environments depending on the context being presented by the

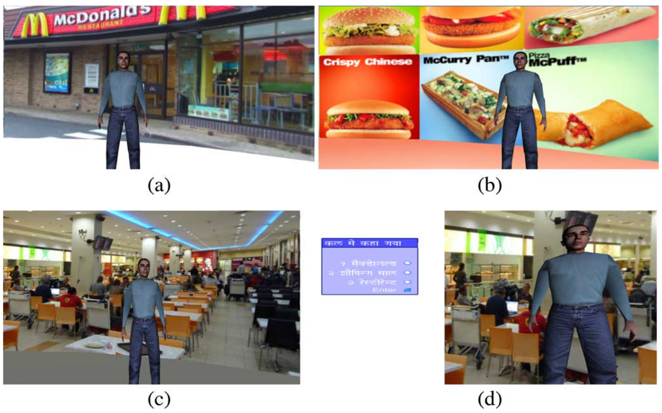

Fig. 2. Screenshot of an example for avatar narrating a story with conversation menu appearing at the end of task presentation.

TABLE III
LIST OF QUESTIONS AT EACH LEVEL

DL	Question Type (No.)	Brief Description
DLI	CR (5)	CR questions are direct and address contexts referred by the avatar during Task Presentation.
DLII	CR (3); PC (2)	CR questions similar to Level I. For PC questions, one needs to do some deduction from facts mentioned in the narration before responding to the question.
DLIII	CR (2); PC (2); ER (1)	CR and PC questions similar to Level II. , ER question was used to understand whether a participant was able to recognize the emotion exhibited by the avatar during narration.
DLIV	CR (2); PC (1); ER (1); PF (1)	CR, PC and ER questions similar to Level III. PF related question was designed to understand the participant's own feeling while listening to the avatar.

Note: CR: Context Relevant; PC: Projected Contingent; ER: Emotion Recognition; PF: Personal Feeling; DL: Difficulty Level

avatar during task presentation. These backgrounds underwent smooth transition based on the context being narrated by the avatar while the avatar moved dynamically in the VR demonstrating gestures and context-relevant emotional expression. The intent was to expose the participant to real-life social scenarios. Fig. 2(a)–(c) shows an example of task presentation module in which the avatar narrates his experience of going to a McDonald's outlet. The avatar initiated the conversation in a traditional way and maintained a social distance of 4.5 feet, appreciated among the Indian population, particularly when speaking to friends for the first time [17]. While the avatar narrated his experience, the background projected the avatar standing in front of the McDonald's outlet [Fig. 2(a)]. When the avatar spoke about his preferences of McDonald's favorites, the avatar walked over towards the counter which advertised different food items, e.g., burgers, wraps, etc., available at the restaurant [Fig. 2(b)]. Finally, when the avatar narrated his experience on table manners and the cleanliness maintained at the outlet, the VR environment displayed such a situation to the participant [Fig. 2(c)]. This task presentation stage was followed by the participant's response to the avatar's questions.

4) Participant's Response Interface: After the avatar narrated his personal experience, the avatar invited the participant into an interaction when a menu-driven interface was presented to the participant. The participant's performance was evaluated based on his response to the avatar's questions while using the menu-driven interface [Fig. 2(d)], designed in Devanagiri script. The participants were asked five questions in succession, each with three response options for them to choose from for each story being narrated by the avatar. The type of questions (details in Section II-B) asked decided the level of task difficulty. Such a menu-driven interface, frequently used by the interactive fiction community [18], provided a ready reference for participants by which they were requested to respond to the avatar's questions by selecting the relevant option. The lawnmower problem in which a user can move through the entire conversation tree, a disadvantage associated with menu-driven systems [18], was overcome in our present work by preventing the participant from tracing back the conversation tree. After the participant's response, VAST provided visual feedback on the participant's performance.

B. Task Switching Rationale

The VR-based social communication system was designed to be adaptive to the participant's performance in a task. The VAST system consisted of four levels of task difficulty and the task switching was based on the participant's performance score at each level. The selected 24 stories (Section II-A2) were distributed among the four difficulty levels (I-IV) with six stories (two stories each for avatars displaying happy, angry and neutral faces while narrating the stories) in each difficulty level. The difficulty level was based on the type of questions (five questions for each story) asked to the participant, e.g., whether these were "context-relevant" (CR), "projected contingent" (PC), "understanding other's emotion," i.e., emotion recognition (ER) and "reporting on one's own feeling," i.e., personal feeling (PF) and their combinations (Table III). For example, let us consider a scenario in which an avatar shared his experience of his visit to McDonald's situated close to his school during the busy lunch time. The CR questions would be on the food items and table manners that were discussed by the avatar. The PC questions would be on purchasing the food coupon from the menu counter. Thus, one of the valid response options would be to stand in a queue to procure the food coupon. Here the participant has to understand that during busy lunch time, he should not rush and create commotion, but be calm and get his food while maintaining social etiquettes. If the avatar's experience at the McDonald's was pleasant, the avatar displayed a happy facial emotional expression. The question on ER was to indicate the participant's ability to identify the avatar's emotion. The question on PF was asked to know the participant's feeling when exposed to this social situation. Specifically, understanding the other's (avatar's) emotion and reporting on one's personal feeling being some of the core deficits of the adolescents with ASD were chosen by us as ingredients of conversation in tasks of higher difficulty levels [2]. A participant's performance was considered "Adequate" (condition: C1 in Table IV) if his score $\geq$70%. Otherwise the performance was considered as "Inadequate" (condition: C2 in Table IV). Our VAST system offered tasks to the participant which switched based on the performance score using a state machine representation (Fig. 3) [19]. As shown in Fig. 3, if a participant was in DLI and his performance was "Adequate" (represented by C1) then the system offered him with

TABLE IV
TASK SWITCHING MECHANISM

Performance	Action Taken
Adequate	C1: Difficulty level ↑
Inadequate	C2: Difficulty level ↓

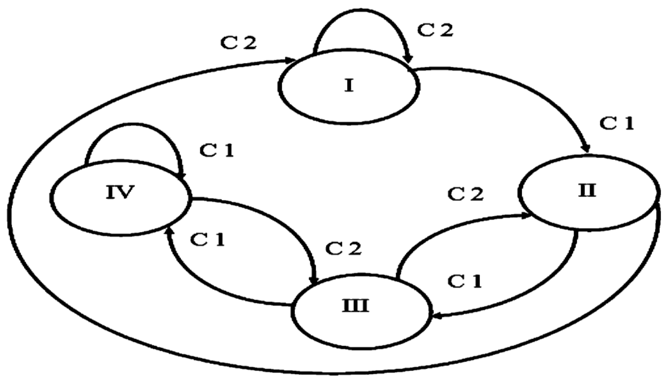

Fig. 3. State machine based task switching rationale. C1—Adequate; C2—Inadequate.

a task of greater challenge (DLII), otherwise, it offered a DLI task (this being the lowest difficulty level). If a participant was in DLII/DLIII and his performance was "Adequate" then the system offered him a task with a greater challenge (DLIII/DLIV, respectively), otherwise, it offered a task of a lesser challenge (DLI/DLII, respectively). When the participant was in DLIV and his performance was "Adequate" then the system offered a DLIV task (this being the highest difficulty level), otherwise, it offered a task of lesser challenge (DLIII). This continued until all the stories in a particular level were depleted. The questions in each level of task difficulty were assigned scores in such a way that in order to achieve a total score that was "Adequate" in each level, the participant had to correctly respond to the more difficult question(s) specific to that difficulty level. Note that this percentage performance score (70%) and the number of questions asked were taken as a first approximation and these can be easily adjusted according to the therapist's suggestions.

C. *Physiological Data Acquisition Module*

While the participant interacted with the VAST system, his physiological signals, e.g., pulse plethysmogram (PPG), skin temperature (SKT), and electrodermal activity (EDA) were monitored using Biopac MP150 in the wireless mode. Markers were used to synchronize the physiological data with each VR-based task. The signals were acquired through LABJACK U3 from Biopac MP150 at a sampling rate of 1000 Hz. Fig. 4 shows a bird's eye view of the VAST system comprising the VR-based module interfaced with physiological data acquisition module.

Pulse plethysmograph (PPG) is a noninvasive technique that records the blood volume pulse waveform via optical methods. The PPG can measure changes in sympathetic arousal [14]. Studies show that the PPG signal measured at the distal phalange of the nondominant hand's middle finger can serve as an indicator of one's anxiety level [14]. The PPG sensor is attached to one's middle finger using a Velcro-strip (Fig. 5).

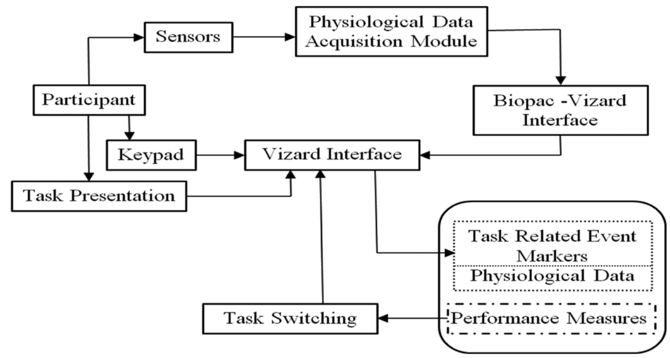

Fig. 4. Bird's eye view of the VAST system.

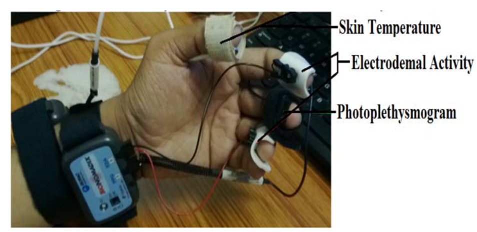

Fig. 5. Sensor setup for physiological data acquisition.

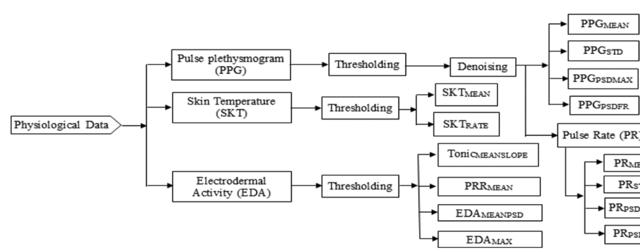

Fig. 6. Block schematic of feature extraction of physiological indices from raw physiological signals.

TABLE V
FEATURES EXTRACTED FROM PHYSIOLOGICAL SIGNALS

Physiological Signal	Extracted features
Pulse Plethysmogram (PPG)	Average of PPG (PPG_{MEAN}), Standard Deviation of PPG (PPG_{STD}), Spectral density of PPG (PPG_{PSDMAX}, PPG_{PSDFR}), Average of Pulse Rate extracted from PPG (PR_{MEAN})), Standard Deviation of Pulse Rate (PR_{STD}), Spectral density of Pulse Rate (PR_{PSDMAX}, PR_{PSDFR})
Skin Temp. (SKT)	Average of SKT (SKT_{MEAN}), average of derivative of SKT (SKT_{RATE})
Electrodermal Activity (EDA)	Tonic slope ($Tonic_{MEANSLOPE}$), Phasic Response rate (PRR_{MEAN}), average spectral power in the frequency band of >0 to ≤2.4 Hz($EDA_{MEANPSD}$), Maximum amplitude (EDA_{MAX})

The skin temperature (SKT) sensor, which is attached to one's thumb using a Velcro strip, measures the peripheral skin temperature. The skin temperature also can be considered as an indicator of one's anxiety level [14]. The electrodermal activity (EDA) sensors, attached to the index and ring fingers of one's nondominant hand, record the skin conductivity and this is also a well-known psycho-physiological measure to detect one's anxiety level [14]. These physiological signals were processed (Fig. 6) and 13 features were extracted. Table V summarizes the various extracted physiological features.

1) Extracting Features From Raw PPG Signal: The raw PPG signal was preprocessed to remove noisy peaks by thresholding. Further processing was done using interval-dependent denoising [20] of the signal. From this denoised PPG waveform, we extracted the pulse rate (PR) (measured from finger tips). Subsequently, we extracted eight PPG related features, e.g., mean amplitude and standard deviation of PPG signal, mean and standard deviation of pulse rate, and maximum amplitude and frequency of their spectral components (Table V and Fig. 6).

2) Extracting Features From Raw SKT Signal: The raw SKT signal was processed to remove noise spikes using thresholding. This signal was subsequently processed to extract two SKT related features, such as mean skin temperature and mean rate of change of skin temperature (Table V and Fig. 6).

3) Extracting Features From Raw EDA Signal: The EDA signal composed of two main components, e.g., tonic and phasic, was processed to extract four features. The mean tonic slope and phasic response rate were extracted after removing the noise spikes from the raw EDA signal. Additionally, we extracted the average spectral power in the frequency band of >0 to ≤ 2.4 Hz and also the maximum amplitude component of the EDA signal (Table V and Fig. 6).

4) Psycho-Physiological Implication: In this study real-time physiological signals were acquired in a synchronized manner with the VR-based task propagation while the participants interacted with VAST for subsequent offline analysis. The aim was not only to understand whether our VR-based system was capable of causing variations in one's physiological indices, but also to understand the psycho-physiological implication, i.e., whether such variations can be related to one's affective state such as, anxiety. Only then will our VR-based system have a potential to contribute towards an effective physiology-based anxiety-sensitive social communication training platform for the target population. Literature indicates the potential of some physiological indices, e.g., SKT, PR, or EDA, to be related to one's anxiety level. Specifically, variations in SKT can be due to localized changes in blood flow caused by arterial blood pressure [10] varying due to anxiety. The PR derived from PPG increases with anxiety [14]. Further, the measurement of EDA can be used to discriminate a user's instantaneous changes in the level of anxiety [11]. In our present work, we have also acquired SKT, PPG and EDA signals while the participants interacted with VAST and subsequently tried to relate the physiological indices to the participants' anxiety level in Section IV-E.

III. Experiment and Methods

A. Participant

Two adolescents with high-functioning autism spectrum disorder (ASD1 and ASD2) and three typically developing (TD1, TD2 and TD3) adolescents participated in our preliminary feasibility study. Adolescents with ASD were recruited through referrals from nearby NGO's and special needs schools and TD adolescents were undergraduate students in our institute. Adolescents with autism were found to be above the clinical thresholds on the Childhood Autism Rating Scale 2nd Edition—High Functioning (CARS 2-HF) [21]. CARS 2-HF is promising as a diagnostic measure because of its simplicity, conceptual relevance, high accordance with DSM-IV diagnosis of autism, and utility among different populations [21]. It is a 15-item behavior-rating scale in which each item is scored on a Likert scale from 1 (no signs of autism) to 4 (severe symptoms). The maximum possible score in CARS 2-HF is 60 and individuals with scores of 28 to 33.5 are rated on mild-to-moderate autism scale and 34 to 60 on severe autism scale. Literature indicates that a threshold score of ≥ 33 is considered as a diagnostic cutoff score to identify cases of autism in the Indian population [22]. Thus both the participants ASD1 and ASD2 having the characteristics as shown in Table VI can be considered to be above the clinical thresholds. ASD1 was in the severe autism range and ASD2 marginally in the mild-to-moderate range. With regard to language and verbal intelligence the TD participants were not tested. ASD2 had scored 88 on Mallin's Intelligence Test [23]. For ASD1 this score was not available. However, ASD1 was enrolled in the same grade at a regular school as ASD2.

TABLE VI
Participants' Characteristics

	Age (years)	Gender	CARS Score
ASD1	17	Male	35
ASD2	17	Male	32.5
TD1	18	Male	-
TD2	18	Male	-
TD3	23	Male	-

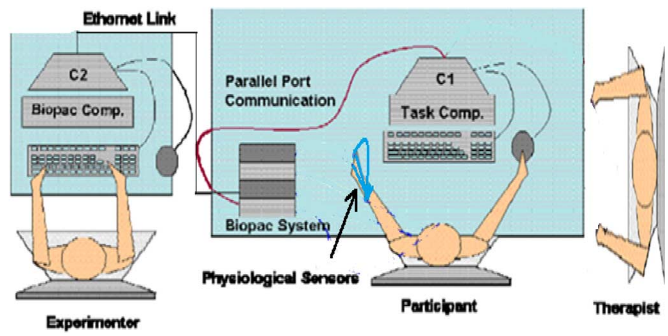

Fig. 7. Experimental setup for VAST system.

B. Experimental Setup and Procedure

We designed the social interaction platform of the VAST system using the Vizard software from Worldviz, Inc. As mentioned in Section II, the VR-based task presentation module consisted of communication tasks each of which ran for approximately 90 seconds followed by the participant's response to avatar's questions. While the participant took part in our study, his physiological signals were acquired using Biopac MP150. Fig. 7 shows the experimental setup. In this the participant was asked to be seated in front of a task computer (C1 in Fig. 7) which executed the VR-based tasks. The participant's physiological signals (PPG, SKT and EDA) were acquired by using the data acquisition module. These physiological signals were transmitted via an Ethernet link and stored in the Biopac computer (C2 in Fig. 7). The participant's physiological signals were synchronized with the VR-based tasks with the help of markers. A clinical observer was also involved in this study for the participants with ASD for grading them on the autism measures (such as, CARS 2-HF).

Initially the experimenter briefed the participant about the study using a visual schedule and demonstrated the experimental setup. The visual schedule indicated the steps involved in the study. This included pictorial representations of the initial instruction, avatar in VR environment showing gestures and finally asking questions to the participant through a menu-driven prompt. This was used to familiarize the participant to the VR-based task progression. The experimental setup comprising of the task computer and the physiological data acquisition system was demonstrated to the participant to get him accustomed with the setup. The experimenter confirmed whether the participant had fully understood the task in which he would take part before proceeding to receive the consent. This was followed by the participant's verbal and written consent regarding his willingness to take part in this study. For the participants with ASD, verbal consent was also obtained from their parents. Additionally, the participant was told that he can withdraw from the study at any point if he felt uncomfortable in interacting with the system. Then, the participant was asked to be seated comfortably on a chair in front of the task computer. After this the physiological sensors were attached to the participant's body. Then the experimenter checked to see whether physiological signals acquired by the data acquisition system were proper. When the participant expressed his readiness to interact with our VAST system, an introductory message scripted in Hindi was presented accompanied by its prerecorded audio file. This introductory message informed the participant that he will be asked to watch and listen to avatars narrating their personal experiences after which the participants would be invited to respond to avatar's questions. Also the participant was asked to imagine that the avatars were like his classmates at school. At first, baseline recording of the participant's physiological signals were made for approximately 3 minutes. Then an avatar appeared in the VR environment and after introducing himself, he went on to narrate his personal experience. Thereafter the participant's performance score was evaluated by the system based on the participant's response to the avatar's questions. Based on this performance score, the system provided feedback to the participant regarding his performance and presented tasks of varying challenges to the participant. Institute ethics was followed for this study.

IV. Results

A. System Acceptability

We investigated to determine whether our VAST system was acceptable to our participants. This initial feasibility study was conducted with two adolescents with ASD and three TD adolescents. In spite of having the freedom to withdraw from the study, all participants completed the tasks. An exit survey questionnaire was administered to know the participant's experience while interacting with the VR-based tasks, their interest to interact with the system again, whether they would suggest their friend interact with our system and whether they have any take-home lessons. The participants reported that they were comfortable wearing the physiological sensors, were able to understand the stories narrated by the avatars and enjoyed responding to the questions asked by the avatars. Both the participants with ASD also mentioned that they liked most of the stories but disliked a few stories in which the avatars displayed angry emotion. One of the participants with ASD mentioned that the system was "motivational". When asked about his notion of being motivational, he said, he liked interacting with our system due to which he was motivated to use our system once again. All the participants enquired about the future possibilities of taking part in this study and expressed that their friends would also find the system interesting. In the present study the questions in the exit survey were subjective. Thus, from our findings from exit survey, we can infer that our system has a potential to be accepted by the target population.

TABLE VII
Analysis of Percentage Performance Score Based on Difficulty Level

	Difficulty Level (DL) - No. of Trials– Avg.Performance (%)
ASD1	DLI – 3 – 80; DLII – 6 – 85.7; DLIII – 6 – 69.1; DLIV – 6 – 59.5
ASD2	DLI– 1– 100; DLII – 2 – 85.7; DLIII – 4 – 80.9; DLIV – 6 – 83.3
TD1	DLI– 1– 100; DLII– 1 – 71.4; DLIII– 2– 100; DLIV – 6 – 85.7
TD2	DLI– 1– 80; DLII– 4 – 92.9; DLIII– 6 – 76.2; DLIV– 6 – 80.9
TD3	DLI – 1– 100; DLII– 2 – 85.7; DLIII– 4 – 89.3; DLIV– 6 – 87.5

B. Potential of Our VAST System in Eliciting Variation in Participants' Performance Score

We analyzed the data from our preliminary feasibility study to understand the potential of our system to elicit variations in the participants' performance. The system switched tasks between four difficulty levels (DLI–DLIV) depending on the participant's performance score during each task trial. Most of the participants showed an improvement in percentage performance score from first to last trial (Table VIII). However, each participant completed the tasks in a different number of trials. Also the time taken by each participant to complete the task was different (Table VIII). The participants with ASD took more time (average 47 min) to complete the tasks than the TD participants (average 37 min).

Further investigation revealed that though the participants found trials in each difficulty level interesting and challenging (from exit survey) the average percentage performance score of all the participants (except TD2 for whom the increase was marginal) decreased from trials of DLI to those of DLIV with variations in score in the intermediate levels (Table VII). This shows that the trials of different difficulty levels were capable of causing variations in the participants' performance score.

C. Potential of Our VAST System of Varying Difficulty Levels in Eliciting Variation in Participants' Physiological Signals

As mentioned in Section II-C, the participants' physiological signals were measured and analyzed. We used statistical tests

TABLE VIII
PERFORMANCE FOR INITIAL AND FINAL TRIAL

	SS (%)	ES (%)	Trials (No.)	TD (min)
ASD1	60	100	21	55
ASD2	100	100	12	40
TD1	100	85.71	10	29
TD2	80	85.71	17	45
TD3	100	100	13	37

Note: SS—Start Score; ES—End Score; TD—Total duration

TABLE IX
PHYSIOLOGICAL FEATURES BASED ON DIFFICULTY LEVEL FOR ASD1

	Features* (No.)			DL Compared
	CV	SKT	EDA	
A	5	0	1	DLI-DLIV
	3	0	2	DLI-DLIII
	3	0	0	DLI-DLII
	0	0	0	DLII-DLIV
	0	1	0	DLII-DLIII
	0	0	0	DLIII-DLIV
H	2	0	2	DLI-DLIV
	2	1	2	DLI-DLIII
	2	0	2	DLI-DLII
	1	1	0	DLII-DLIV
	3	1	0	DLII-DLIII
	0	0	1	DLIII-DLIV
N	1	0	1	DLII-DLIV
	0	0	1	DLII-DLIII
	0	0	0	DLIII-DLIV

Note: A—Angry, H—Happy, N—Neutral, DL—Difficulty Level

TABLE X
PHYSIOLOGICAL FEATURES BASED ON DIFFICULTY LEVEL FOR ASD2

	Features* (No.)			DL Compared
	CV	SKT	EDA	
A	0	1	1	DLIII-DLIV
H	1	0	0	DLIII-DLIV
N	0	0	0	DLI-DLIV
	0	0	0	DLI-DLIII
	0	0	0	DLI-DLII
	2	0	0	DLII-DLIV
	0	0	0	DLII-DLIII
	0	0	0	DLIII-DLIV

Note: A—Angry, H—Happy, N—Neutral; DL—Difficulty Level, $^*p < 0.05$.

TABLE XI
PHYSIOLOGICAL FEATURES BASED ON DIFFICULTY LEVEL FOR TD1

	Features* (No.)			DL Compared
	CV	SKT	EDA	
A	0	0	0	DLI-DLIV
	0	0	0	DLI-DLII
	0	0	0	DLII-DLIV
H	2	0	1	DLIII-DLIV
N	0	1	0	DLIII-DLIV

Note: A—Angry, H—Happy, N—Neutral; DL—Difficulty Level, $^*p < 0.05$.

TABLE XII
PHYSIOLOGICAL FEATURES BASED ON DIFFICULTY LEVEL FOR TD2

	Features* (No.)			DL Compared
	CV	SKT	EDA	
A	0	0	0	DLII-DLIV
	0	0	0	DLII-DLIII
	0	0	1	DLIII-DLIV
H	1	1	0	DLI-DLIV
	5	0	0	DLI-DLIII
	0	0	0	DLI-DLII
	0	0	1	DLII-DLIV
	1	0	0	DLII-DLIII
	0	0	0	DLIII-DLIV
N	0	0	0	DLII-DLIV
	0	0	0	DLII-DLIII
	0	0	0	DLIII-DLIV

Note: A—Angry, H—Happy, N—Neutral; DL—Difficulty Level,$^*p < 0.05$

such as a dependent sample t-test to find the physiological features that varied statistically with the degree of difficulty of VR-based trials. Prior to testing for statistical significance we tested the data for normal distribution using the Shapiro-Wilk test for normality. From this test we were assured that most of the physiological features corresponding to different difficulty levels were normally distributed. For the t-test, we first segregated the participants' physiological signals corresponding to trials of different difficulty levels, while keeping the emotions displayed by the avatars constant. Such categorization was done for data analysis to ensure that the variation in physiology was only due to variation in difficulty levels. Tables IX–XIII show the physiological features that were statistically significantly different between trials of different difficulty levels. The results show that our VAST system caused statistical variations in 17 physiological features for "angry" expression demonstrated by the avatars, 21 for "happy," and 2 for "neutral" avatars' faces for participants with ASD. Likewise, for TD participants, results show that there was statistical variation in 5 physiological features for "angry," 12 for "happy" and 7 for "neutral" faces. Not only the physiology was affected, but also the percentage performance scores of both the ASD and TD groups varied with degree of difficulty. However, for both the physiology and performance scores, the effect of our VAST system was more pronounced for the ASD group as compared to the TD group. While going deeper in carrying out the comparative analysis between ASD1 and ASD2, the results from Table IX and Table X show that cumulatively (considering cases for happy, angry and neutral emotions) a greater number of physiological features (38) of ASD1 varied with trials of different difficulty levels compared to 5 features for ASD2. Trying to find an explanation into such a discrepancy between ASD1 and ASD2, we found that the CARS 2—HF score indicated that ASD1 belonged to severe autism range compared to ASD2 who was on mild-to-moderate autism scale. However, with a data sample of limited power, we cannot generalize our findings.

D. Potential of Our VAST System to Cause Variation in Participants' Physiological Signals in Response to Different Avatar Emotions

Although our system was not designed to train our participants in emotion recognition, with our study data we investigated the effect of emotions demonstrated by the avatars on the participants' physiology. We tested the statistical significance of extracted physiological features on two emotions (e.g., happy and angry) that are on the two opposite sides of the valence

TABLE XIII
PHYSIOLOGICAL FEATURES BASED ON DIFFICULTY LEVEL FOR TD3

	Features*(No.)			DL Compared
	CV	SKT	EDA	
A	0	0	2	DLI-DLIV
	0	0	0	DLI-DLIII
	0	0	0	DLI-DLII
	1	0	1	DLII-DLIV
	0	0	0	DLII-DLIII
	0	0	0	DLIII-DLIV
H	0	0	0	DLIII-DLIV
N	5	0	1	DLII-DLIV
	0	0	0	DLII-DLIII
	0	0	0	DLIII-DLIV

Note: A—Angry, H—Happy, N—Neutral; DL—Difficulty Level, $^{*}p < 0.05$.

scale, while keeping the difficulty levels constant for each analysis. In general, for all the participants, a smaller number of physiological features corresponding to avatars' emotions were statistically different. This can be attributed to the fact that the avatars' emotions during our VR-based social communication were very subtle in nature. Interestingly, we observed that ASD1 had a greater number of physiological features that were statistically significant (Table XIV) than that for ASD2 and his other TD counterparts. From this we can infer that the subtle emotions demonstrated by the avatars did not have any significant effect on TD adolescents and ASD2. However, ASD1, belonging to the severe autism range (Table VI), was affected to a greater extent by the emotional expressions of the avatar during task presentation. This was based only on our observation with no intention to infer any connectivity between severity of autism and influence of emotional expression with the limited sample of the present study. Although emotion recognition is one of the core social deficits in ASD, our primary aim of this study was not to understand the emotion-recognition capability of the participants. However, since we used the emotion-recognition in the questionnaire of tasks of higher difficulty, we analyzed further to evaluate if emotion-recognition capability increased among the participants with task progression. For ASD1, the capability to recognize avatars' neutral and happy emotions improved with task progression. However such improvement was not observed for angry emotion for ASD1. For ASD2, there was an improvement in the recognition capability for all three emotions. The TD participants on the other hand came with better emotion-recognition capability and showed minor improvements with task progression.

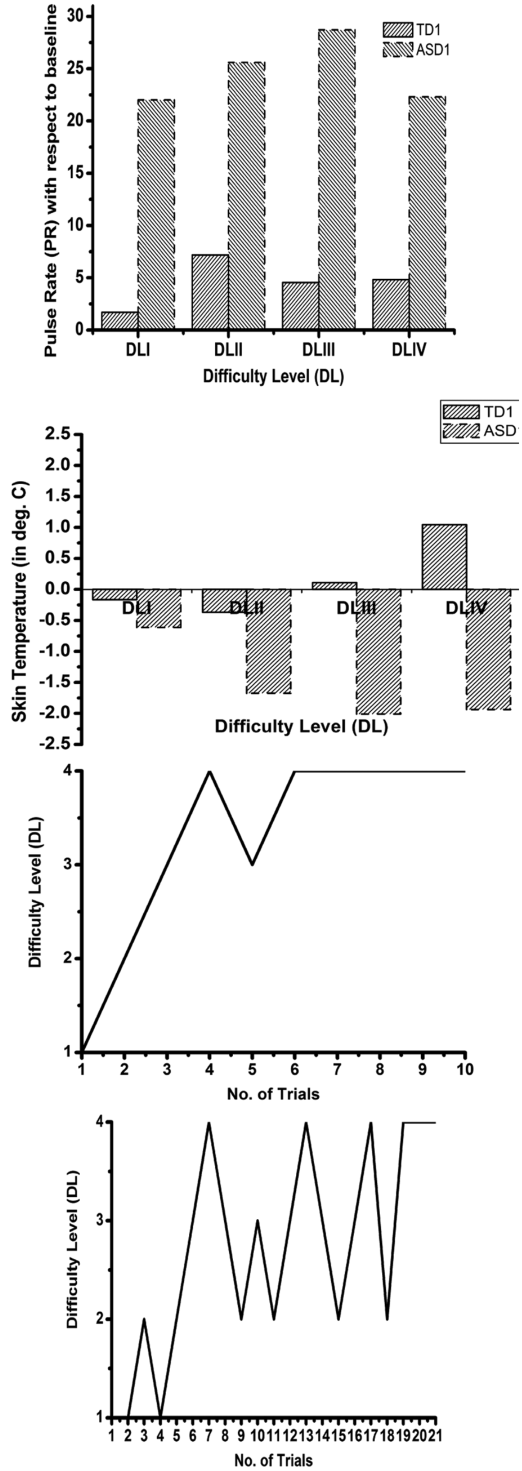

Fig. 8. Experimental setup for VAST system.

E. Understanding Underlying Rationale Between Physiological Indices and Performance Measure

In order to understand the underlying rationale that connects the participants' performance and physiology, we selected ASD1 and TD1 for further analysis. We selected one pair of participants in order to present an in-depth analysis of data. As an example, we selected mean values of pulse rate ($\mathrm{PR_{MEAN}}$) and skin temperature ($\mathrm{SKT_{MEAN}}$), even though these features were not consistently statistically significant across trials of different difficulty levels (as can be seen from Tables IX–XIII). From Fig. 8, we observe that for ASD1, the $\mathrm{PR_{MEAN}}$ increased and $\mathrm{SKT_{MEAN}}$ decreased progressively with respect to the baseline condition from DLI to DLIII and these indices ultimately settled down by the time he interacted with task of DLIV. However, for TD1 (Fig. 8), we find that the variation in the trend of $\mathrm{PR_{MEAN}}$ and $\mathrm{SKT_{MEAN}}$, while interacting with trials of different difficulty levels, indicate a different picture from that of ASD1. Studies show that one's increased anxiety level is often manifested as an increase in $\mathrm{PR_{MEAN}}$ and decrease in $\mathrm{SKT_{MEAN}}$ [24]. Thus, we can infer from the above that the anxiety level of ASD1 while interacting

TABLE XIV
PHYSIOLOGICAL FEATURES BASED ON AVATARS' EMOTIONS

	Features* (No.)		
	CV	SKT	EDA
ASD1	3	0	1
ASD2	0	0	0
TD1	0	1	1
TD2	2	0	0
TD3	0	0	0

$^{*}p < 0.05$.

with trials of varying difficulty was higher compared to that of TD1. We analyzed further to see the effect of anxiety level (as manifested through physiology) on the participants' percent performance scores and the task progression of the VR-based trials. From Table VII, we find that for ASD1, the percent performance score on an average showed a decreasing trend (except minor increase in DLII). For TD1 on the other hand (Table VII), we find that the average percent performance score showed a decreasing trend from DLI to DLII and also from DLIII to DLIV. We analyzed further to study the nature of task progression of the VR-based task for ASD1 and TD1. ASD1 completed interaction in 21 trials (Fig. 8) in 55 min (Table VIII) with frequent switching between trials of different difficulty levels. For TD1, the task progression was complete within 10 trials in 29 min (Table VIII) with lesser switching between trials of different difficulty levels. The above observation can also be attributed to the variations in one's anxiety level which is manifested through variations in one's physiological indices.

V. CONCLUSION

Autism is a neurodevelopmental disorder characterized by a triad of impairments in socialization, communication and imagination. The deficits in social interaction and communication skills impact an individual's ability to develop friendships, initiate and maintain conversation, respond appropriately [25], interpret body language and facial expressions [26]. Deficits in these skills create barriers for individuals with ASD in successful participation in community life at later stages leading to social isolation. Anxiety disorders in these adolescents may be considered both as possible cause and consequence of their social communication deficit. In conventional intervention settings, the therapist continuously monitors one's anxiety level in order to effectively decide the floor-time-therapy. The basic intent is to provide a comfortable/less anxiety-inducing learning platform for these adolescents. Here we designed VAST, a technology-assisted VR-based social communication platform. Here we addressed some of the core deficits in social communication skills through participation in social situations where the adolescents interact with their virtual peers narrating social stories. Our VAST system has the potential to use one's real-time physiological signals as markers of his anxiety level. At the end of each task, our system reported the participant's performance as feedback.

As a proof-of-concept application, we have designed a usability study in which two adolescents with ASD and three TD adolescents interacted with our VAST system. The preliminary results revealed that VAST system was capable of causing variations in the participants' performance score and physiological signals. In fact, both the task difficulty level and the avatars' emotional expressions had individual effects on the participants' physiology. This can serve to have a preliminary understanding of the underlying rationale between performance measures and physiology which in turn can be mapped to one's anxiety level. This understanding is essential for designing a comfortable social communication skill-learning platform that can adapt itself to one's anxiety level. For the VAST to be a comfortable social skill-learning platform it must: 1) provide real-life representation of social communication scenarios while addressing social communication norms and 2) rather than being only performance driven, it should be sensitive and adaptive to one's anxiety level. Reduced anxiety infers greater comfort [27] which in turn fosters improved learning. Our proof-of-concept study shows the feasibility of VR-based social communication to have implications on one's performance and physiology which can be used as bio-markers of his anxiety level. In future, we plan to design our system so that it would be intelligent enough to adjust itself based on one's anxiety level predicted from his physiology. This might in the long run help one to get exposed to realistic social situations, and also foster scaffolded learning of social skills by allowing him to operate from his comfort zone.

Though the preliminary results are encouraging, our initial study had some limitations. While the participants interacted with VAST system, we acquired their physiological signals for later offline analysis. Our system offered tasks of varying challenges to the participant based only on his performance without taking into consideration his anxiety level. Incorporating the anxiety level of the participant harnessed from his physiological signals in the task switching rationale would have provided an increased individualization for the system. Also, our study had a limited sample size with which we cannot generalize our findings. In addition, in our present study, the inclusion of the participants with ASD was done on the basis of CARS-2HF scores. No other structured diagnostic and IQ evaluation scores were available with us. A detailed in-depth study needs to be carried out involving more participants. In future, we plan to recruit participants with ASD having structured diagnostic and IQ evaluation scores. In addition, both of our participants with ASD belonged to the high-functioning spectrum. Involving participants in the low-functioning category would require refinement of some of the hardware used in our study. In future, we plan to augment our system by adding a speech recognizer module so that the participants with low-functioning ASD need not use mouse/keyboard while communicating with the VR world. The participants enrolled here were adolescents with autism, since we required the participants to understand different aspects of social communication with an inherent complexity. Specifically, our participants were expected to understand the subtle social nonverbal cues, such as facial emotional expression, correlate it with social context, respond to projected-contingent questions where they were required to think and deduce responses from facts drawn from the narration. Responding to such questions with inherent social complexity would be appropriate for adolescents who have already received some level of exposure to the social norms while participating in their daily living activities, such as attending schools, birthday parties, mixing with friends, etc.

In the future, we believe that our system will have the potential to serve as a complementary tool in the hands of the therapist who can: 1) get an understanding of one's physiological profile; 2) enjoy the flexibility to expose the individual to different social scenarios even at her clinic; and 3) administer the social skill training to more than one individual at a time by using multiple computers running the VR-based program. The research work presented here serves as a first step towards realizing the potential of VR-based social communication platform to cause variations in one's performance and anxiety level that can be mapped from one's physiology. In the future, we plan to augment the capability of our system with physiology-based anxiety-sensitive adaptive feature having higher degree of individualization which might have greater potential to contribute to improved social communication capability of these adolescents. In the long run, we hope that such an individualized VR-based platform can contribute at least partially to addressing some of the core social communication deficits of these individuals thereby helping them to lead a productive life.

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