

Adaptive Virtual Reality for Autism: A Heart Rate Driven Sensory Regulation System Using Large Language Models

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Abstract—Autistic individuals often experience sensory hypersensitivity, making immersive virtual environments potentially overwhelming without adaptive regulation. This work presents a novel adaptive virtual reality (AVR) framework that dynamically adjusts environmental stimuli based on real-time physiological indicators, supported by lightweight large language models (LLMs). The system combines (1) heart rate driven sensory modulation, (2) an Unreal Engine therapeutic scenario with fully parameterized lighting and sound controls, and (3) an AI-driven conversational agent capable of delivering calming guidance and interactive support. A heart rate classification pipeline, implemented using gpt-4.1-nano-2025-04-14, transitions the environment between overstimulating (red, loud soundscape) and calming (blue, reduced volume) profiles, while a unified LLM prompt generates brief single-paragraph relaxation cues during heightened arousal. A second pipeline integrates speech-to-text, LLM reasoning, and text-to-speech to enable continuous natural interaction inside VR. Early testing with simulated physiological data demonstrates the system's ability to detect stress patterns, adjust sensory variables in real time, and produce coherent therapeutic responses. Although full user validation and integration with real physiological sensors remain ongoing, these results indicate that coupling VR with LLM-driven adaptive control offers a promising foundation for accessible, personalized, and regulation-supportive immersive environments for autistic users.

Index Terms—Extended reality, augmented reality, virtual reality, artificial intelligence, machine learning, large language model, accessibility, people with disabilities

Identify applicable funding agency here. If none, delete this.

I. INTRODUCTION

Individuals with autism spectrum disorder (ASD) frequently experience differences in sensory processing, often displaying heightened sensitivity to visual, auditory, and proprioceptive stimuli compared to neurotypical individuals [12]. As a result, environments that are loud, bright, or unpredictable can easily become overwhelming, triggering stress responses or sensory overload. These challenges extend beyond physical spaces into virtual platforms as well [15]; immersive environments such as virtual reality (VR) can unintentionally amplify sensory intensity due to their highly vivid and enveloping nature [14]. Although VR offers developers extensive control over environmental variables—such as lighting, texture density, sound levels, and spatial complexity—these adjustments are traditionally static or pre-designed due to limitations in computational resources, especially on head-mounted displays (HMDs), and the original intent of the environment. Adaptive Virtual Reality (AVR) seeks to overcome these constraints by dynamically modifying sensory factors in real time based on the user's physiological or behavioral responses. By adjusting stimuli as the user begins to show signs of overstimulation, AVR can help maintain comfort, reduce stress, and support more inclusive and accessible immersive experiences for individuals with sensory sensitivities, particularly those on the autism spectrum.

Building on this idea, a large language model (LLM) can

serve as an adaptive layer that helps regulate the sensory intensity of a VR environment [9]. By interfacing directly with the VR software, an LLM can trigger real-time environmental adjustments—such as dimming lights, lowering ambient noise, or simplifying visual complexity—once it receives the appropriate signals. This is particularly important because autistic users who become overstimulated may struggle to verbally express discomfort or request specific environmental changes. Traditional LLMs rely primarily on explicit verbal or written commands, meaning they are not naturally equipped to interpret non-verbal cues such as facial tension, avoidance of eye contact, or body language. However, integrating physiological signals—most notably heart rate—provides a more objective and continuous indicator of stress or sensory overload. Elevated heart rate is strongly correlated with sympathetic nervous system activation, making it a valuable signal that can automatically inform the LLM when the user is overwhelmed. In addition to adjusting the environment, the LLM can act as a therapeutic conversational agent, offering calming guidance, grounding techniques, or supportive dialogue to help the user regain comfort while remaining immersed in the virtual experience. This combination of physiological monitoring and intelligent interaction creates a more responsive, accessible, and user-centered VR system for individuals with sensory sensitivities.

In order to assess this theory, this study will create an environment in VR and simulate a user's heartbeat as they are faced with sensory input that could provoke stress, such as intense lighting and sounds. An AI agent (based on GPT 4.1-nano) will assess the stimulated heart rate, and if it's elevated, therefore indicating stress, the agent will reduce the environment's lighting and sound until the user has calmed down, and talk to the user to help them calm down.

II. BACKGROUND AND RELATED WORK

Adaptive virtual reality (AVR) is a form of virtual reality where the environment can be altered in real-time, usually to ensure a better user experience. These alterations can be manual, where the user requests an alteration, or automatic, following alternative input from the user. AVR can be used to help people with disabilities utilize VR with more ease. Cabrera-Araya and Rojas-Munoz [2], for instance, posit that the environment can be altered so that people with upper limb impairments can reach for virtual objects.

According to systematic reviews [5], a considerable amount of virtual reality applications for autistic users are focused on healthcare and education [16], most with environments designed to help the user navigate situations that may be difficult in a controlled setting, such as social interactions, exposure therapy [8] and navigating unknown environments. However, given that these environments are developed with autistic users in mind, many focus on reducing stimuli whenever possible. This can posit a challenge when more stimulating VR applications do not have accessibility features that can reduce the stimuli when needed.

Heart rate (HR) is often used as an objective metric for a user's psychological state in VR. With this type of metric, some studies have analyzed comparative data and have found that VR experiences can lead to lower average HRs compared to 2D screens [6]. HR is also a reliable stress tracker in therapeutic applications, like for Virtual Reality Exposure Therapy (VRET) for social anxiety. VR environments can elicit different HRs, and the stress levels caused by them can be adapted in real-time by manipulating responses from virtual characters interacting with the user. Other VRET studies, which also depend on HR, are also trying different approaches for capturing this type of data with less equipment, like predicting HR from head movements alone.

To the best of our knowledge, this is the first study using an LLM-based system in real time to reduce stimuli in VR for users with ASD. Reviews, such as Maddalon et al. [10] and Blackmore et al. [1], analyzed AVR interventions for autistic children and biofeedback and AI in extended reality, and no studies used LLMs for autistic users.

III. RESEARCH METHOD

This study follows a multi-stage methodological approach designed to investigate, implement, and evaluate an adaptive virtual reality (AVR) environment capable of dynamically responding to sensory overload in autistic users. The process brings together literature review, physiological modelling, VR development, artificial intelligence (AI) pipelines, and early-stage iterative testing. To build a technically grounded and clinically relevant system, each stage was developed sequentially, with insights from one phase informing decisions in the next.

The first stage involved a systematic review of academic literature on virtual reality applications for individuals with autism spectrum disorder (ASD), with particular attention to systems that incorporate adaptive sensory features. This examination made it possible to identify existing theoretical frameworks, therapeutic VR protocols, and current technological constraints related to real-time modulation of sensory stimuli such as lights, colors, and sound intensity. These findings provided the initial conceptual foundation for designing an adaptive VR environment capable of responding to signs of sensory overstimulation.

Building upon this, a second literature review focused on clinical perspectives regarding the distinction between a "sensory crisis" state and a "normal" sensory state in individuals with ASD. The goal was to understand how clinicians define and detect these states and to identify physiological metrics that reliably correlate with sensory distress. Heart rate patterns emerged as the most consistent and clinically supported indicator of escalating arousal, offering a practical physiological signal for driving adaptive behaviors in VR.

A third review further explored empirical studies on how specific types of visual and auditory stimuli—particularly color schemes, brightness levels, sound frequency, and ambient noise—affect emotional regulation in autistic individuals. This review was essential in determining which environmental

parameters should be prioritized for dynamic adjustment and what kinds of sensory modulation are most likely to promote comfort, reduce overstimulation, or help restore regulation during a crisis.

Informed by these three bodies of literature, a virtual scenario was then developed using Unreal Engine. The environment was deliberately designed to support dynamic manipulation of lighting, color palettes, and auditory elements, enabling rapid and smooth transitions controlled by external inputs.

An artificial intelligence pipeline was subsequently implemented using gpt-4.1-nano-2025-04-14 to interpret simulated heart rate data. This pipeline analyzes incoming physiological values, classifies the user's state (e.g., baseline or heightened arousal), and automatically adjusts environmental elements—including environmental color and sound volume—within the Unreal Engine environment. The purpose of this adaptive control loop is to mitigate overstimulation and create a more supportive sensory context for autistic users, allowing the environment to adjust in real time without requiring the user to verbalize their discomfort or explicitly request sensory modifications.

Parallel to this, a second AI pipeline was developed, also using gpt-4.1-nano-2025-04-14, to support natural and therapeutic interaction with users. This conversational system provides real-time responses to questions, doubts, and spontaneous comments, offering a communicative layer that can help guide, reassure, or ground the user during challenging sensory moments. The interaction model was designed to maintain clarity, warmth, and emotional safety, reflecting best practices in ASD-sensitive communication.

Finally, the integrated system is undergoing iterative testing. These ongoing trials focus on assessing the responsiveness of adaptive adjustments, the coherence of environmental transitions, and the quality of the conversational experience. Although still in progress, this phase aims to refine the AVR framework, verify its technical robustness, and evaluate its potential applicability in therapeutic or clinical contexts.

IV. ADAPTIVE VR SYSTEM ARCHITECTURE DESIGN

The following section presents a comprehensive overview of the system's architecture and implementation, detailing all components that support the adaptive virtual reality environment. Each subsystem—from the Unreal Engine scenario and sensory-modulation controls to the AI pipelines responsible for physiological monitoring and user interaction—is described individually to clarify its role, functionality, and integration within the complete application. This breakdown provides the necessary technical context to understand how the system operates as a cohesive adaptive framework.

A. Heart Rate as a Primary Indicator of Sensory Stress

A central design decision in the system architecture was the adoption of heart rate activity as the primary physiological variable guiding real-time sensory adaptation in the virtual environment. This choice is grounded in clinical literature

indicating that autonomic arousal—particularly elevations in heart rate and reductions in heart rate variability—is one of the most consistent and quantifiable markers of sensory overload in individuals with autism spectrum disorder (ASD) [3]. Unlike verbal or behavioral indicators, which may be delayed, masked, or difficult for autistic users to express during moments of overwhelm, cardiac signals provide a continuous, objective, and non-verbal measure of stress [13]. Heart rate also offers practical advantages for system implementation: it can be captured at high frequency, processed efficiently, and mapped to intensity thresholds that reliably differentiate baseline states from sensory crisis states. For these reasons, heart rate dynamics were selected as the foundational metric for triggering adaptive adjustments to lighting, color saturation, and auditory intensity throughout the VR environment.

The development and validation of the adaptive pipeline were conducted using simulated heart rate data. This allowed the system to reliably trigger and observe the full cycle of environmental adaptation—including color transitions, auditory modulation, and guided therapeutic feedback—without depending on live physiological sensors. For this purpose, a predefined heart rate sequence was constructed to mimic a typical progression from a neutral baseline state to an overstimulated, arrhythmic pattern and then back toward recovery. The vector *SEQUENCY_BPM*

```
"""
SEQUENCY_BPM = [55, 55, 56, 55, 58,
59, 55, 57, 58, 56, 56, 56, 56, 100,
100, 99, 99, 99, 101, 101, 99, 99,
101, 99, 98, 98, 100, 101, 85, 87,
87, 87, 85, 84, 84, 73, 75, 75, 75, 72]
"""
```

was selected to replicate a user who begins in a calm, regulated physiological state, enters a period of elevated arousal and instability when exposed to red lighting and aversive sound cues, and then gradually returns to a more stable rhythm as the environment transitions to calming blue tones and the AI-based therapist provides guided relaxation. This simulated pattern ensured that all adaptive and interactive components of the system could be fully demonstrated during development.

B. Evidence-Based Selection of Colors and Sounds for Adaptive VR

Research on sensory processing in autism consistently shows that visual and auditory characteristics—such as color wavelength, brightness, contrast, pitch, and sound intensity—have measurable effects on emotional regulation and arousal [11]. Individuals with ASD often exhibit heightened sensitivity to certain colors and frequencies [4], while responding more positively to others that promote calmness or predictability. Drawing on this body of evidence, our system incorporates a deliberate mapping between environmental stimuli and regulatory goals: red hues are used to signal heightened arousal or stress detected through physiological monitoring, while the accompanying soundscape increases in

volume to intentionally amplify sensory load and reflect an overstimulated state. Conversely, blue tones are employed to induce a calming effect and stabilize sensory processing, paired with a reduced-volume soundscape designed to lower auditory intensity and support the user's return to a regulated state. [7]. This evidence-based approach ensures that the dynamic VR adaptations are not arbitrary, but grounded in established principles of sensory modulation for autistic individuals.

C. Virtual Scenario

The virtual scenario was developed in the Unreal Engine as a controlled therapeutic consultation room designed to simulate a safe, familiar, and clinically coherent environment for autistic users. The choice of a therapy-room setting reflects its frequent use in real-world behavioral and sensory regulation sessions, thereby offering a valid context for evaluating adaptive interventions. The room includes standard therapeutic elements such as a comfortable chair, minimalistic furniture, soft ambient lighting, acoustic treatment, and a neutral visual layout to avoid unnecessary sensory load. Some environmental assets—including lighting sources and sound emitters—were configured to allow real-time parameter manipulation by the adaptive system. This includes dynamic adjustments of color temperature, hue shifts, brightness, and spatial audio intensity, enabling the AI pipeline to modify the environment based on heart rate input and sensory regulation goals. By constructing a fully parameterized and interactable environment, the scenario serves as a testbed where sensory stimuli can be systematically modulated and observed without compromising user safety or immersion.

D. Adaptive AI Pipeline for Heart Rate Driven Sensory Modulation

The first artificial intelligence pipeline was designed to interpret the user's physiological signals—specifically heart rate values—and convert them into adaptive modifications of the virtual environment. Implemented using the model gpt-4.1-nano-2025-04-14, this pipeline continuously receives heart rate inputs and classifies them into one of two physiological states: **baseline** or **alert**. Once classified, the system triggers predefined sensory adjustments. When the signal corresponds to a baseline state, the environment transitions to a red lighting scheme and increases ambient sound levels, reinforcing the contrast needed for testing adaptive responsiveness. Conversely, when the heart rate is interpreted as an alert state, the pipeline shifts the virtual environment to a calming configuration by changing the ambient lighting to blue, reducing the volume of environmental sound, and initiating the guided auditory relaxation routine. The verbal component of this calming response is generated through a compact therapist-oriented prompt, as follows, which instructs the model to produce continuous, succinct, single-paragraph therapeutic guidance tailored for ASD-sensitive stress modulation. When the pipeline detects a transition toward an overstimulated state,

it automatically applies this calming profile, as illustrated in Figure 2.

```
"""
You are a cognitive-behavioral therapist
specialized in ASD.
If the patient is showing signs of
physiological stress
(elevated heart rate), act as a stress
guide, using short and welcoming
calming-breath cues.
Be empathetic the entire time.

CRITICAL RULES (MUST FOLLOW EXACTLY):
1. DO NOT USE ANY NEWLINES. Treat
"\n" as a forbidden character.
2. DO NOT BREAK LINES. Write everything
in one single paragraph.
3. DO NOT USE DOUBLE SPACES.
4. DO NOT FORMAT WITH BULLETS, LISTS, OR
LINE BREAKS.
5. Produce a calm, continuous
single-paragraph sentence
structure.
"""
```

E. AI-Interaction Pipeline

To enable natural, continuous, and therapeutically guided interaction within the adaptive VR environment, a second integrated AI-driven communication pipeline was developed, capable of processing user speech, generating therapeutic responses, and transmitting them back to the virtual setting in real time. This pipeline combines automatic speech recognition and a conversational LLM therapist within a single feedback loop. Incoming audio is first transcribed using a speech-to-text (STT) module based on OpenAI's Whisper. These inputs are then passed to a therapist-oriented LLM prompt and the generated response is subsequently converted into speech through a text-to-speech (TTS) by ElevenLabs ChatBot Integrator (Unreal) subsystem, allowing the user to hear the therapist's answer directly within the VR environment, thereby completing the interactive loop.

The full interaction pipeline is summarized in Figure 1, which illustrates how each module communicates with the others within the integrated AVR framework.

V. LIMITATIONS

The development of this adaptive VR framework remains ongoing, and several limitations and threats to validity must be acknowledged. Most notably, the system currently operates using simulated heart rate data, which—although useful for controlled testing—cannot fully reflect the variability, irregularity, and noise present in real physiological signals. A real user's heart rate patterns may diverge significantly from the predefined sequence used to validate color transitions and AI-driven therapeutic responses. Furthermore, user testing and

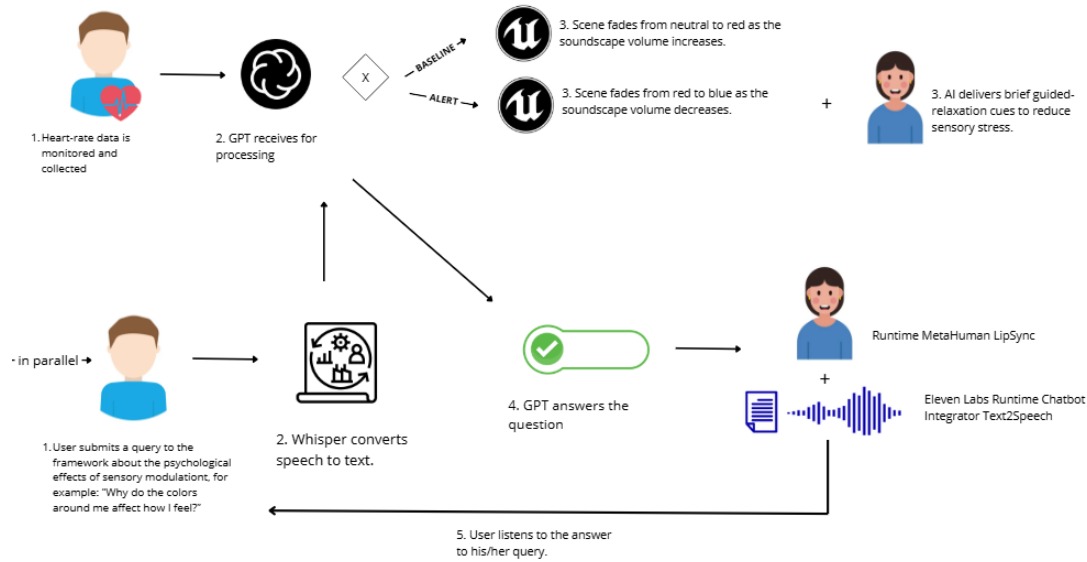


Fig. 1. End-to-end AI-driven adaptive interaction pipeline for immersive VR therapy. Physiological signals (e.g., heart-rate variability) are continuously monitored and processed by a therapist-oriented LLM to infer user state (baseline vs. alert). Based on this inference, the VR environment dynamically adapts audiovisual parameters in Unreal Engine (e.g., color gradients and soundscape intensity) and may deliver brief guided relaxation cues. In parallel, user spoken queries are transcribed via Whisper (STT), semantically processed by the LLM, and rendered back to the user through ElevenLabs text-to-speech with real-time MetaHuman lip-sync, enabling naturalistic, closed-loop therapeutic dialogue within an adaptive virtual environment.

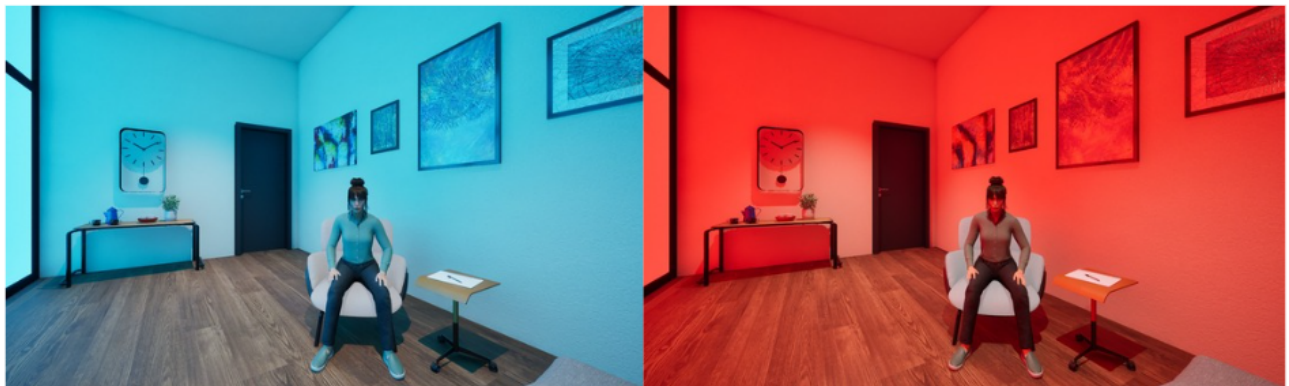


Fig. 2. Dynamic color modulation in the adaptive VR environment, transitioning from overstimulation (red) to a calming state (blue) based on heart-rate-driven AI control.

empirical validation of the full system are still underway, meaning that the current results represent an initial technical demonstration rather than confirmed behavioral or clinical outcomes. These constraints frame the context within which the final considerations and future directions should be interpreted.

VI. FINAL REMARKS

This work presented the design and early implementation of an adaptive virtual reality framework capable of responding dynamically to indicators of sensory overload in autistic users. By integrating physiological monitoring, real-time environmental modulation, and an AI-driven therapeutic companion,

the system demonstrates the technical feasibility of creating immersive environments that both detect and mitigate overstimulation. Although the current prototype relies on simulated heart rate data and remains in the early stages of user testing, the results highlight the potential of combining VR with lightweight large language models to support neurodiverse users in emotionally demanding scenarios. The methodological pipeline—spanning literature-informed design, Unreal Engine development, sensory adaptation strategies, and multimodal AI interaction—lays the groundwork for a future clinically validated tool. Continued development will focus on collecting real physiological signals, conducting systematic user studies,

refining the adaptive thresholds, and expanding the repertoire of sensory interventions. Taken together, these efforts aim to advance adaptive VR toward a robust, evidence-based resource for therapeutic, educational, and assistive applications in autism and beyond.

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