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The Role of Auditory and Visual Stimuli in Stress Perception and Sensory Preference within Virtual Environments

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***Abstract*— The purpose of this study is to explore the individual and combined effects of auditory and visual stimuli on stress perception within Virtual Reality (VR). The exploration utilized physiological measures as Blood Volume Pulse (BVP), psychological assessments like the State-Trait Anxiety Inventory-Short Form (STAI-S), and NASA Task Load Index (NASA-TLX). Participants were immersed in two contrasting VR environments. The first environment was a tranquil forest, whereas the second scene was a chaotic city. Participants' stress levels under different sensory conditions were assessed methodically by switching between congruent and incongruent audio-visual experiences. The findings of this study contribute to our understanding of sensory impacts on stress perception in VR environments and to the development of individualized VR experiences specific to individuals' sensory preferences. While the findings suggest some individual variability in stress responses, particularly in audio versus visual stimulus dominance, these observations were not statistically significant, indicating a need for further exploration into personalized sensory experiences in VR.**

Keywords— Virtual Reality (VR), Immersive Environments and Presence, Stress, Audio-Visual Stimuli.

I. Introduction

As virtual reality (VR) technology continues to make significant advancements, it presents a distinctive avenue for exploring how sensory experiences within a virtual environment (VE) can elicit physiological responses like those experienced in the physical world [1] [2]. Researchers can deepen into the complex relationship between sensory inputs and physiological reactions by replicating realistic scenarios within an immersive virtual realm. This technology not only empowers the examination of psychological responses in diverse simulated environments but also supports therapeutic interventions aimed at enhancing individuals' ability to effectively manage their stress responses [3].

To gain a comprehensive understanding of human psychological responses, it is essential to grasp the dynamic interplay between stress and environmental factors [4], including both auditory and visual elements [5]. These environmental factors have a substantial impact on our emotional well-being, resulting in varying levels of anxiety and stress. However, the influence of environmental factors on human stress levels remains largely unexplored, warranting further investigation [6]. Despite virtual reality's predominant emphasis on the visual aspect, it is plausible that auditory stimuli also contribute to stress perception. This fundamental inquiry raises the question: Is stress perception in a VE primarily dependent on visual elements, or do auditory components also play a pivotal role? Consequently, one of the primary objectives of this study is to unravel the distinct and combined effects of audio and visual stimuli on stress perception within VE.

Furthermore, individuals exhibit diverse responses to sensory stimuli, with some individuals being more visually oriented while others are more attuned to auditory cues [7] [8]. An individual's sensory preference could potentially influence his/her stress levels, prompting an important question: Can physiological measurements differentiate these individual variations? The second objective of this study is to explore the answer to this question.

Recent efforts to measure stress or anxiety have relied on either subjective questionnaires or objective physiological assessments. For instance, Jones explored the use of physiological classifiers in augmented reality and VR training scenarios, demonstrating the potential for adapting the training based on learners' stress responses [9]. Orozco-Mora et al. examined how VR games affect participant's stress levels using ECG, EDA, and EMG signals [10]. Additionally, Bosse et al. investigated the effects of virtual training on stress responses, reporting significantly lower emotional intensity among

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Fig. 1. Designed virtual environments: Forest vs. City.

participants who underwent virtual training [11]. Extending this line of research, Kamińska et al. delved into the use of EEG signals for classifying stress levels within a VR context [12]. Moreover, Blood Volume Pulse (BVP) and Photoplethysmogram (PPG) have been utilized to classify stress levels [13] [14] [15]. However, the impact of audio and visual components on the perception of stress and their subsequent effects on physiological responses remains unknown.

In this study, we concentrate on the influence of sensory stimuli, specifically auditory and visual cues, on the perception of stress within Virtual Environments (VE). Additionally, we explore how individuals with diverse sensory preferences react to these stimuli. To accomplish this, we conducted an empirical study in a VE, exposing participants to both congruent and incongruent visual and auditory stimuli. We employed a comprehensive approach, utilizing subjective assessments like the State-Trait Anxiety Inventory-Short Form (STAI-S) [16] and the frustration component from the NASA Task Load Index (NASA TLX) [17], along with physiological measurements such as BVP, to gauge stress levels. These dual assessments enable us to quantitatively evaluate the physiological impact of sensory stimuli while shedding light on how individuals emotionally and psychologically perceive and interpret these stimuli. We anticipate that the correlations between objective and subjective measurements will provide insights into the influence of sensory preferences on stress perception. Consequently, our study makes two primary contributions:

- **Sensory Impact Research**: This study provides insights into how visual and auditory stimuli affect stress perception in VEs. It advances our understanding of the role played by these senses in triggering stress responses by isolating their effects.
- **Personalized Stress Response Analysis**: This study illustrates how a person's sensory preferences (visual or auditory) can influence his/her stress perception, enabling more personalized VR experiences.

II. Methods

We conducted an empirical study where human participants were engaged within a virtual environment (VE).

A. Participants

A total of 22 healthy individuals (7 females and 15 males with age 26.08 $\pm$ 4.5 years) participated in the study. All participants were students at the University of Calgary, possessed normal vision, and reported no prior neurological or cognitive disorders. The study was conducted with an ethical clearance from the University of Calgary, and all participants provided their informed consent before participating.

B. Experimental Setup

The study utilized the Oculus Rift S headset (Display**:** Fast-switch LCD 2560×1440, with a per-eye resolution of 1280 x 1440 pixels, a 94-degree field-of-view, and an 80Hz refresh rate) to interact with the VE. Additionally, an Empatica E4 bracelet was used to record the participants' physiological data. The VE was developed using Unity 3D (2020.3.26f1). Two distinct environments – forest and city – were designed to modulate the participants' stress levels; since prior studies suggest that natural spaces like forests reduce stress [18] and people prefer brighter, sunnier settings [19], whereas the city environment is linked to higher stress [19].

Forest Environment: As shown in Fig.1 - Forest, the forest ambiance was designed to evoke a sense of tranquility. The visual scene comprised a hut with a lake and forest view, a well-furnished cabin, and all interconnected by paths. Moreover, birds were flying in different directions.

Sounds included gentle forest noises, lake water, wind, and bird chirps. This setting was illuminated to mimic a bright, sunny day, fostering a feeling of relaxation.

City Environment: In contrast to the forest environment**,** the city ambiance was designed to emulate a tense and chaotic urban setting, as shown in Fig. 1 - City. This involved incorporating loud sounds from vehicles, sirens, rain, and running people.

The visual scene portrayed burning buildings, heavy rainfall, and bustling pedestrians. This setting was lit to resemble a dim, moody urban night, further intensifying the chaotic sensation.

Navigation Method: We devised an automated navigation approach by leveraging an animator system to maintain uniform exposure to the VE. This choice was made to eliminate any possible discrepancies that might arise from teleportation or other navigation methods, thus guaranteeing a consistent assessment of the environment's impact on the participants.

C. Procedure

The study was conducted in a quiet room. Each participant was asked to relax in a serene setting, seated comfortably for a span of 10 minutes. Following this relaxation period, we recorded their baseline physiological data. The study was structured into two phases: the reference conditions and the conflict conditions. Each phase was comprised of two blocks corresponding to a city and a forest environment. Each block lasted for 2.5 min, with a 5 min rest interval between them. Participants were advised to refrain from any sudden movements or actions during these phases.

Reference Conditions: During this phase, the participants were exposed to a congruent experience in which the visual and auditory stimuli were synchronized. There were two reference conditions: "city_ref" and "forest_ref". In the "city_ref" condition, the participants were presented with visuals of fires, barking dogs, and running people paired with their corresponding sounds. Likewise, in the "forest_ref" condition, the participants observed the visual scene of lakes and flying birds with the appropriate sounds of water and birds chirping.

Conflict Conditions: The purpose of this phase was to assess the participants' sensitivity to incongruent audio-visual elements within the VE. To do so, we combined the visual scene of one environment with the auditory sounds of the other. There were two conflict conditions: "city_conf" and "forest_conf". In the "city_conf" condition, the participants observed the chaotic city visual scene while being exposed to the tranquil sounds of the forest. In the "forest_conf" condition, the participants viewed the serene forest scene but were subjected to the discordant sounds of the city.

The physiological data – Blood Volume Pulse (BVP) – of each participant were collected continuously while the participant was engaged with the VE. We administered the STAI-S questionnaire to assess the participant's stress levels and the NASA-TLX questionnaire to measure his/her frustration after each block. Both the STAI-S and NASA-TLX are widely used tools for behavioral assessments of stress and mental-emotional effort, respectively. In this study, we integrated physiological data with these tools to establish a correspondence between behavioral and physiological stress responses.

D. Feature Extraction and Analysis:

We employed Python 3.8 along with the pyhrv function to extract important features from the BVP data. The features encompassed the Root Mean Square of Successive Differences between normal heartbeats (RMSSD), the mean heart rate (HR-mean), and the standard deviation of the N-N interval (SDNN) [20]. RMSSD provides insights into short-term heart rate variability and often reflects parasympathetic activity. An increase in RMSSD typically indicates a more relaxed state, while a decrease may suggest heightened stress. Conversely, an upsurge in heart rate (HR-mean) is commonly associated with increased stress levels. Lastly, SDNN reflects overall heart rate variability. A reduced SDNN can imply decreased adaptability and possibly increased stress, whereas an elevated SDNN value is indicative of a potentially relaxed state.

Apart from examining physiological (objective) data, we also analyzed subjective data, i.e., STAI-S and NASA-TLX. We assessed the normality of the data using the Shapiro-Wilk test [21], revealing that both subjective and objective data did not meet the criteria for normality and homogeneity. Consequently, we opted for non-parametric testing methods, specifically the Wilcoxon Signed Rank test for comparing each

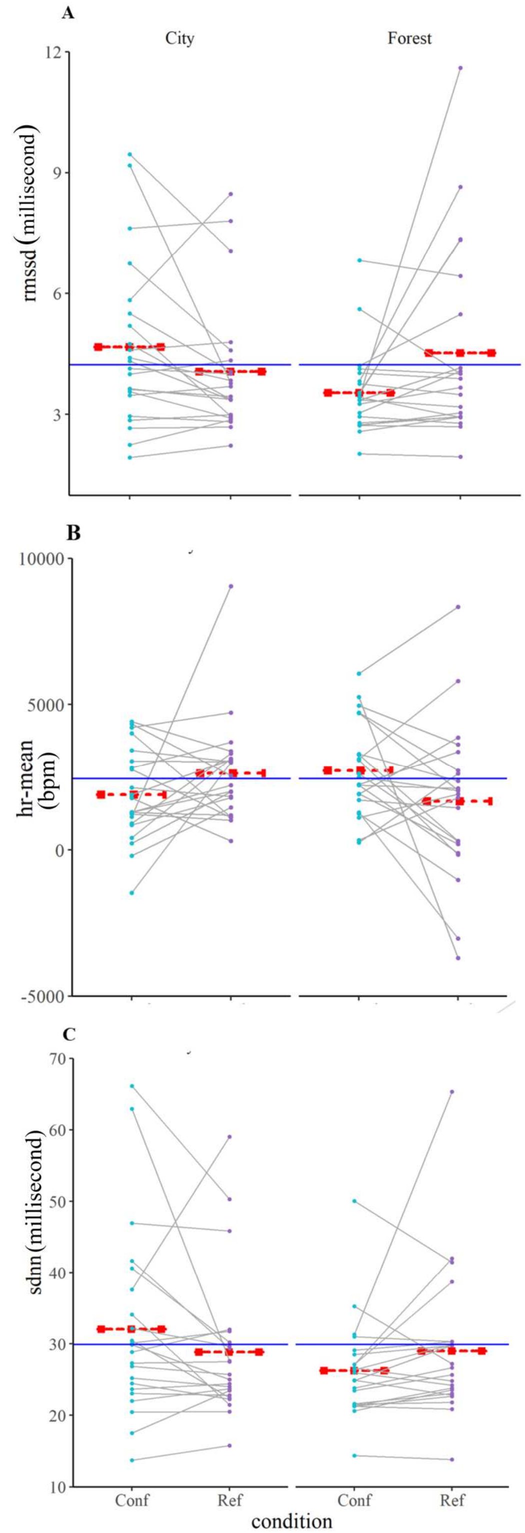

Fig. 2. Comparison of "RMSSD"," HR-mean", and "SDNN" values across City and Forest environments under 'Conf' and 'Ref' conditions, with individual data point trajectories. The unit of RMSSD and SDNN is milliseconds (ms), while the unit of HR-mean is beats per minute (bpm). [Note: The blue straight line represents the mean value of the baseline condition, while the red dotted line represents the mean value for each condition.

TABLE I. THE MEAN AND STANDARD DEVIATION OF THE FEATURES

	RMSSD	***HR_mean***	***SDNN***
City_ref	4.66 ± 2.06	1903 ± 1577	32.08 ± 13.18
City_conf	4.06 ± 1.65	2642 ± 1786	28.86 ± 10.28
Forest_ref	3.53 ± 0.03	2733 ± 1589	26.25 ± 6.96
Forest_conf	4.52 ± 2.36	1676 ± 2642	29.03 ± 10.51
Baseline	3.39 ± 1.08	2450 ± 2000	29.90 ± 11.75

pair of conditions. A 'Z' value for each set of paired comparisons was presented to serve as a crucial statistical metric, quantifying how many standard deviations a particular result is from the dataset's mean. Essentially, this 'Z' value is a measure of deviation, assisting us in evaluating the significance of differences observed between the paired comparisons. This test is ideal for such data, as it doesn't assume normal distribution and helps determine whether there are significant differences between pairs of observations. All statistical analyses were performed using IBM SPSS software (version 26).

III. RESULTS

This section contains the results of the objective evaluation followed by the subjective evaluation. Since our physiological data and questionnaire responses didn't follow a normal distribution and weren't homogeneous, we used the Wilcoxon Signed-Rank Test for comparing each pair of conditions.

A. *Objective Evaluation*

RMSSD: Regarding RMSSD, Fig. 2A presents a connected scatter plot illustrating RMSSD for both reference and conflict conditions. Each point represents the RMSSD value of an individual participant, and the line connecting the points indicates changes in RMSSD values between the paired conditions for the same participant. This plot reveals that the average RMSSD increased from city_ref to city_conf, suggesting a decrease in stress levels. Conversely, the average RMSSD decreased from forest_ref to forest_conf, indicating an increase in stress levels. Yet, the pattern varies from individual to individual. Table I provides the mean and standard deviation values for RMSSD in different conditions.

We conducted a Wilcoxon Signed Ranks Test comparing RMSSD for all possible pairs of conditions, as outlined in Table II. Surprisingly, no pairwise comparisons showed a significant difference, except for the city_conf and forest_conf pair. This specific pair exhibits a statistically significant difference in RMSSD [$Z = -2.007$, $p < 0.05$].

HR-mean: In Fig. 2B, it is evident that the average HR-mean among the participants decreased when transitioning from the city_ref to city_conf conditions, signifying a reduction in stress levels. Conversely, the average HR-mean increased when transitioning from forest_ref to forest_conf conditions, indicating an elevation in stress. Table 1 presents the average HR-mean values with their corresponding standard deviations. These HR-mean results align with the RMSSD outcomes.

Table II displays the results of the Wilcoxon Signed Ranks Test, revealing significant differences for each condition when compared to the baseline condition. However, no significant

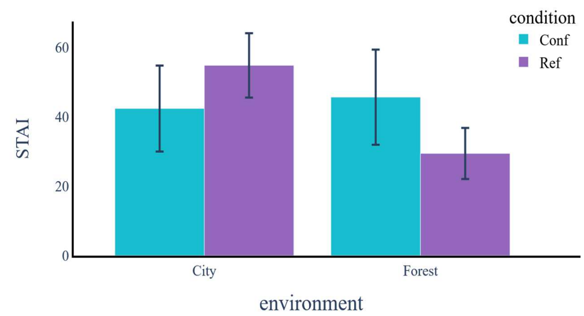

Fig. 3. Bar graph displaying the mean anxiety levels in different conditions measured by the STAI. Error bars represent standard deviation.

differences were observed between the reference or conflict conditions.

SDNN: Fig. 2C depicts a graphical representation of SDNN across four conditions. The City environment demonstrated a tendency for increased SDNN values during the conflict condition relative to the reference condition. This is visually represented by a preponderance of descending lines as subjects transition from city_conf to city_ref. This outcome aligns with the outcome of the RMSSD and HR-mean confirming that the stress level decreased in the city_conf condition compared to the city_ref condition. An opposite pattern was observed within the forest environment, where the conflict condition exhibited decreased SDNN measurements in comparison to the reference condition denoting elevated stress. The average SDNN across different conditions is outlined in Table I.

Despite the difference exhibited in the graphical representation, the Wilcoxon test revealed no significant difference between any pair of conditions as shown in Table II.

B. *Subjective evaluation*

STAI: The bar graph in Fig.3 presents a visual comparison of stress levels, as measured by the STAI questionnaires, across two different conditions – conflict and reference – within two distinct environments – city and forest. In the city environment, the reference condition shows a relatively high mean STAI score (54.80±*9.26*), with a moderate level of variability among the participants. This suggests that the participants generally experienced higher stress levels when being not exposed to conflict. Conversely, the conflict condition in the city presents a significantly lower mean STAI score (42.38± *12.38*), albeit with a larger spread in the stress responses. This indicates that the conflict, on average, may have a mitigating effect on stress within the urban setting.

The forest environment paints a different picture. Here, the reference condition boasts the lowest mean STAI score of all scenarios (29.43 ± *4.35*), indicating lower stress levels in a forest setting without conflicts. However, when a conflict is introduced, the mean STAI score increases to 45.65 ± *7.35* with a moderate level of variation among the participants. This shows that a conflict has an elevating effect on stress levels in the forest compared to the city environment.

TABLE II. OUTCOMES OF THE WILCOXON SIGNED RANK TEST

Pairs	RMSSD		HR-mean		SDNN		STAI		NASA-TL Frustration	
	Z	***p***	***Z***	***p***	***Z***	***p***	***Z***	***p***	***Z***	***p***
Baseline – city_ref	0.761	$p > 0.05$	**-3.393**	$\mathbf{p < 0.001}$	-0.456	$p > 0.05$	-	-	-	-
Baseline – city_conf	-1.065	$p > 0.05$	**-3.717**	$\mathbf{p < 0.001}$	-0.791	$p > 0.05$	-	-	-	-
Baseline – forest_ref	- 0.395	$p > 0.05$	**-3.263**	$\mathbf{p < 0.01}$	-0.152	$p > 0.05$	-	-	-	-
Baseline – forest_conf	-1.277	$p > 0.05$	**-3.393**	$\mathbf{p < 0.001}$	-1.247	$p > 0.05$	-	-	-	-
city_ref – forest_ref	- 0.30	$p > 0.05$	-0.503	$p > 0.05$	-0.910	$p > 0.05$	**-4.014**	$\mathbf{p < 0.001}$	**-2.460**	$\mathbf{p < 0.01}$
city_ref – city_conf	-1.095	$p > 0.05$	0.536	$p > 0.05$	-0.760	$p > 0.05$	**-3.023**	$\mathbf{p < 0.01}$	***-0.907***	$p > 0.05$
forest_ref – forest_conf	-0.912	$p > 0.05$	-0.114	$p > 0.05$	-0.973	$p > 0.05$	**-3.875**	$\mathbf{p < 0.001}$	**-2.618**	$\mathbf{p < 0.01}$
city_conf– forest_conf	**-2.007**	$\mathbf{p < 0.05}$	-0.568	$p > 0.05$	-1.612	$p > 0.05$	-1.459	$p > 0.05$	-1.432	$p > 0.05$

Note: There was no baseline for the subjective data – STAI and NASA-TLX, so no comparison was made from the baseline

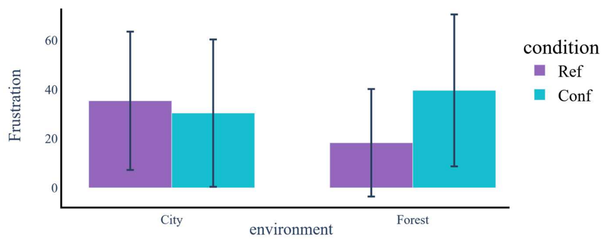

Fig. 4. Impact of environment on frustration: A comparison between Forest and City settings under reference and conflict conditions.

Upon conducting the Wilcoxon signed-rank tests, a statistically significant difference was discerned between the city_ref and city_conf condition [$Z = – 3.023, p < 0.05$] as shown in Table II. Similarly, the results in the forest environment were pronouncedly significant between the reference and conflict conditions [$Z = – 3.875, p < 0.001$]. Moreover, there was a significant difference in STAI score between the city and forest environment in the reference conditions [$Z = – 4.014, p < 0.001$] but not in the conflict conditions.

Frustration: The graph displayed in Fig.4 illustrates the comparison of frustration measured by NASA-TLX across both forest and city environments under two distinct scenarios: reference and conflict.

As seen in the forest environment, the reference condition displays lower frustration than the conflict condition. Comparatively, in the city environment, frustration is decreased for the conflict condition when compared to the reference condition. It is interesting to note that the values for the reference and conflict conditions are quite similar in the city environment, suggesting that the city environment itself may be a source of cognitive stress leading to frustration. In contrast, individuals may experience less cognitive strain unless they are presented with conflicting tasks or information in the forest environment.

As shown in Table II, the Wilcoxon signed ranked test revealed a significant difference in frustration between the forest_ref and forest_conf conditions [$Z = – 2.618$, $p < 0.01$]. However, the difference was not significant in the city environment while contrasting the reference and conflict conditions. In addition, a significant difference was also observed between the forest and city environment in the reference condition [$Z = – 2.460$, $p < 0.01$], but not in the conflict condition. This outcome confirms that the forest environment was less frustrating compared to the city environment for the participants.

IV. DISCUSSIONS

Both subjective and objective assessments emphasize the pivotal role of the environment in influencing stress levels. Notably, the forest setting appears to be less stress-inducing when compared to the city environment, as evident from the lower STAI and frustration scores in non-conflict scenarios. These findings support previous studies that highlight the soothing effects of natural settings like forests over urban areas [19]. Additionally, our research brings a new perspective by examining the impact of congruent and incongruent auditory stimuli within the environments on stress levels.

However, the introduction of conflict (i.e., incongruent auditory stimuli) produces varying effects. Stress levels decreased from the city_ref to the city_conf condition, while increased when transitioning from the forest_ref to the forest_conf condition. This suggests that the impact on stress levels isn't solely attributed to conflict situations; instead, it is contingent on the auditory stimuli. For example, transitioning from city_ref to city_conf involves a shift from chaotic to calm sounds, which reduces stress levels. Conversely, chaotic sounds increased the stress levels in the forest_conf condition compared to the forest_ref condition.

Although the subjective and objective results followed the same trend, we did not observe a significant distinction between the reference and conflict conditions when analyzing objective data. This lack of significance could be attributed to individual variability. As shown in Fig. 2, the stress level increased for the most participants when transitioning from reference to conflict conditions, while some participants exhibited the opposite pattern. This divergence in individual behaviors suggests that some participants may be more influenced by auditory stimuli (audio-dominant), while others may be more influenced by visual stimuli (video-dominant). However, the significant difference in HR-mean observed in both reference and conflict conditions when compared to the baseline conditions is indicative of the sense of 'presence' experienced within the VE. This presence, reflecting variations in stress levels irrespective of whether the stimuli were congruent or incongruent, highlights the impact of environmental factors on psychological responses. Building on this understanding, our study's insights have practical implications for enhancing virtual reality therapies. By tailoring visual and auditory elements to individual needs, these therapies can be optimized for more effective stress management and mental health interventions.

It's important to acknowledge that this study has some limitations. We were unable to induce significant stress among the participants in an experimental setting, as it would violate the clauses of ethics clearance. Consequently, the features of BVP served as indicative but not prominent indicators of significant differences in stress levels across the various conditions. Moreover, this study had 7 females and 15 males among the participants. This gender mix could impact our findings since women and men often react differently to stress. For instance, their physiological responses and coping strategies can vary. Our observations might be skewed with more male than female participants. Future work should aim for a more balanced gender ratio to better understand how VR environments affect different genders and demographics. Notwithstanding, this study provides valuable insights but should be viewed in light of this gender disparity. Further research can delve deeply into gender-specific reactions in VR. In addition, future work needs to involve more sophisticated physiological data such as electroencephalography and Galvanic Skin Response (GSR) besides BVP to understand the effect of congruent and incongruent virtual immersion on stress levels. A correlation analysis among different features is also necessary to eliminate redundant features from future analysis.

V. Conclusion

This study revealed that different environmental settings, such as forest and city, evoke varying stress responses when the settings are further modulated by the presence of conflict sensory stimuli. Notably, the study found that individual responses to stress in VR vary, with some participants being more influenced by auditory stimuli and others by visual stimuli. This variation indicates the necessity of personalized VR experiences to meet individual sensory preferences, especially for therapeutic purposes. Even though being limited in its ability to induce significant stress levels in an experimental setup, the study offers a framework for future research to use sophisticated physiological measures to understand the effect of stress on VR users. Future work includes participant-specific responses under various conditions and involves a diverse demographic sample.

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