Investigating Behavioral and Neurophysiological Responses Across Landslide Scenarios in Virtual Reality

Arjun Mehra[1][a], Arti Devi[1][b], Ananya Sharma[1][c], Sahil Rana[1][d], Shivam Kumar[1][e],
K. V. Uday[2][f] and Varun Dutt[1][g]
[1]Applied Cognitive Science Lab, IIT Mandi, India
[2]Geotechnical Engineering Lab, IIT Mandi, India

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Abstract: The potential of virtual reality for disaster preparedness is enormous, but little is known about how different landslide risks and environmental factors (day versus night) affect human reactions. Neurophysiological (alpha/theta, alpha/gamma, and beta/gamma ratios from EEG) and behavioral (Euclidean distance, collisions, and velocity around collisions) measures are combined in this study to investigate stress and cognitive engagement in landslide simulations. In order to expose 80 participants to varying landslide probabilities, they were randomly assigned to four groups with varying landslide risk and lighting conditions. Behavioral deviations and cognitive workload were significantly influenced by perceived risk rather than lighting conditions, according to the results. Electroencephalography (EEG) and behavioral outcomes were correlated, which emphasized how crucial integral analysis is to comprehending disaster responses. These results demonstrate how well virtual reality can develop cognitive resilience and offer guidance for creating training plans that maximize performance in high-risk scenarios. This study develops dynamic, immersive VR-based disaster preparedness apps.

1 INTRODUCTION

Landslides cause significant global infrastructure damage and fatalities annually, often triggered by human activities or natural disasters like earthquakes and floods, compounding disaster management challenges (Highland, 2008; Petley, 2012). Even with improvements in early warning systems, disaster response is still hampered by the unpredictable nature and quick onset of landslides.

A revolutionary tool for researching human behavior in dangerous, difficult-to-replicate disaster scenarios is virtual reality (VR) technology, which provides immersive and controlled environments (Alene, 2023; Du, 2021). Research indicates that VR-based training improves risk perception, memory, and real-world applicability, frequently matching field training results (Gross, 2023; Adami, 2021).

Prior work only focused on static models and used traditional methods to navigate landslide-prone areas. This research highlighted this issue and addressed this gap by using VR simulations to investigate people's actions and responses in landslide scenarios.

Using virtual reality driving simulations, this study examines how people react physically and behaviorally to landslide threats during the day and at night. It provides a thorough understanding of landslide responses by analyzing participant behavior

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[a] https://orcid.org/0009-0006-0175-3532
[b] https://orcid.org/0000-0002-0171-297X
[c] https://orcid.org/0009-0004-3000-8924
[d] https://orcid.org/0009-0002-7545-5264
[e] https://orcid.org/0009-0008-4816-6006
[f] https://orcid.org/0000-0002-9579-5496
[g] https://orcid.org/0000-0002-2151-8314

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and neurophysiological data (such as EEG). Public awareness campaigns, disaster training initiatives, and the construction of safer infrastructure in landslide-prone areas can all benefit from the findings.

The findings suggest that people's physical and behavioral reactions can be influenced by the level of perceived danger and simulated environment.

The remainder of the paper is organized as follows. First, prior work done in related areas was discussed briefly followed by the research gap. The expectation section included details about behavioral indicators, measures and effects of illumination. In material and methodology, the section briefly discussed the simulation, participants and experimental design. At last, the implications and future research highlighted

2 BACKGROUND

Research on disaster management is being revolutionized by virtual reality (VR), which makes it possible to examine human behavior in risky situations without actual dangers. According to Petley's research, virtual reality can be used to study how people react to landslides, a common and deadly natural disaster that causes a lot of damage (Petley, 2012).

Earthquakes, rain, or human activities like deforestation can cause landslides, which are complicated geophysical phenomena in which material slides down slopes. Effective risk mitigation and disaster response training are essential due to the unpredictable nature of landslides and their abrupt onset (Highland, 2008).

Researchers can evaluate stress levels, attention, and cognitive engagement by examining these EEG frequency bands during disaster simulations, giving them a thorough grasp of how people react under pressure. By pinpointing areas where participants might need more assistance or practice, this method improves the efficacy of training initiatives. EEG has been shown to be useful in assessing mental stress and cognitive workload in earlier research. For example, studies have demonstrated that differences in Alpha, Beta, Theta, and Gamma bands can be used as markers of mental stress, underscoring the value of these metrics in evaluating reactions in disaster drills (Bakare, 2024).

By incorporating EEG analysis into disaster preparedness training, customized interventions that enhance cognitive resilience and performance under stress can be created. This integration ultimately leads to more effective disaster response strategies by facilitating a more nuanced understanding of the neural mechanisms underlying human behavior in emergency situations.

Conventional crisis training is based on static simulations or theoretical scenarios that don't accurately represent the dynamics of actual events. By producing dynamic, immersive environments, virtual reality (VR) overcomes these drawbacks and works well in disaster training scenarios. The effectiveness of disaster preparedness is increased by VR-based fire safety training, which performs better than conventional approaches in terms of application and retention (Smith, 2009).

According to Chittaro and Ranon's research, virtual reality simulations can accurately evaluate and get stakeholders ready for risks, producing outcomes that are on par with field research (Chittaro, 2009). These studies support the usefulness of VR in crisis training, particularly in situations where testing in the real world is risky or impractical.

Although there is evidence to support the use of virtual reality (VR) in disaster training, the majority of research ignores dynamic interactions, such as navigating terrain that is prone to landslides, in favor of static simulations (Takeda, 2005). Realistic training is provided by dynamic scenarios, which improve readiness and emergency response skills. This study fills the gap by using VR-based simulations to investigate reactions to dynamic landslide scenarios.

This study simulates landslide accidents using day-night conditions and probability distributions (low: 0.2, high: 0.8). The study investigates how participants react behaviorally and physiologically to various situations. It uses neurophysiological measurements (such as EEG) and self-reports to gain a thorough understanding of how people react in risky situations.

Through the extension of virtual reality to dynamic, interactive scenarios, this study advances our understanding of human behavior during landslides. The results can be used to inform disaster training programs, public awareness campaigns, and safer infrastructure in landslide-prone areas.

3 EXPECTATIONS

We hypothesized that the perceived danger levels associated with different landslide probabilities would significantly alter the behavioral and neurophysiological responses of research participants. In particular, we anticipated that:

3.1 Behavioral Indicators

Participants exposed to high-probability landslide scenarios would deviate more from their intended driving path, as indicated by the Euclidean Distance (ED) surrounding crashes. Because of the increased perceived danger, this would imply more erratic driving behavior and increased caution. More collisions would occur in high-probability scenarios, suggesting that participants would find it more difficult to navigate the hazardous environment. Participants would probably report faster velocities close to collisions in high-risk situations, despite the possibility that this would lead to less controlled driving and more crashes. This could be a reflexive attempt to quickly move away from perceived risks.

3.2 Measure of Neurophysiology

People would be more nervous and mentally focused on the threat than they are at ease in high-risk situations, according to the Alpha/Theta ratio, a measure of cognitive engagement and alertness. The measured Alpha/Gamma ratio, which is associated with information flow and attention, would also increase. This suggests that comprehending these complex situations requires more mental work. In high-risk circumstances, the Beta/Gamma ratio, which gauges cognitive effort, would likewise rise, reflecting the mental strain that the participants would experience in riskier circumstances.

3.3 Effect of Illumination (Day Versus Light)

We expected that responses would differ substantially depending on the probability of landslides, but that daytime versus nighttime lighting would have less of an impact on the behavioral and neurophysiological measurements. This would imply that the main factor affecting participants' responses in the simulation is perceived danger rather than environmental visibility.

These expectations were based on the knowledge that people's thoughts and actions during disasters are greatly influenced by their perceptions of risk. In order to gain insight into the potential for VR-based training programs to improve disaster preparedness, the study was created to investigate how these elements interact within a controlled virtual reality environment.

4 MATERIALS AND METHODS

4.1 Participants

As seen in Figure 1, 80 participants (60 men and 20 women, mean age = 22, SD = 1) were chosen at random through an advertisement and asked to take part in the study. Informed consent was acquired through a Google form, and participation was entirely voluntary. The only prerequisite for being on the shortlist was being older than eighteen. In addition to having educational backgrounds at least as high as a high school diploma, each participant had a scientific background and obtained intermediate school, bachelor's, master's, and even doctoral degrees. The study's participants received INR 100 in compensation for their involvement.

4.2 Virtual Reality Simulation for Landslide

A virtual reality landslide simulation was created using Unity 2021.3.30f1 with Gaia Pro, Easy Roads 3D Pro, and Realistic Car Controller V3 (Cai, 2023). XR plugins were added to the simulation to enable compatibility with Virtual Reality HMDs, and the Logitech SDK was installed and incorporated into the simulation to enable compatibility with the Logitech steering wheel. According to the manually set landslide probability, which was either 0.2 or 0.8 prior to the participant entering the play mode, the simulation used three colliders to create a landslide when a car entered the landslide-prone area. Gaia Runtime was also used to set the day and night lights before players switched to play mode. The night mode can be accessed with reduced visibility and time perception by adjusting the lighting settings' time, which in turn modifies the position of the Sun, the directional light source. To ensure that noise won't impair participants' ability to drive, the hardware is installed in a quiet lab space with air conditioning.

The participant's goal was to keep the vehicle on the left side of the road and drive it to the end of the road twice. Two C# scripts, positional and collision data recorders, were added to the simulation in order to gather the x, y, and z coordinates of the car's position and collision with a landslide in CSV format. In the parent folder where the project was stored, these scripts stored the files in CSV format.

4.3 Experimental Design

The study complied with the Declaration of Helsinki and received approval from the Institutional Ethics

Committee (World Medical Association, 2013). Participants (N = 20 each) were split into four groups at random:

Group 1: High probability of landslides, during the day
Group 2: High probability of landslides, during the night
Group 3: Low probability of landslides, during the day
Group 4: Low probability of landslides, during the night

Each experiment lasted 10–15 minutes, depending on driving speed of the participant. The collected data encompassed demographic information, an Indian personality questionnaire, risk assessment, evaluation of driving skills and experience, terrain familiarity, weather condition experience, night driving experience, accident history, risk perception, and landslide perception, all gathered subsequent to obtaining consent. Post-simulation evaluations included VR experience quality, driving behavior, realism, situational awareness, confidence, and emotional response. Post-simulation assessments encompassed the quality of the VR experience, driving conduct, realism, situational awareness, confidence, and emotional response. The analyses were performed utilizing an interactive landslide perception and education program executed via a Google form.

Figure 1: A VR landslide sim setup (Night condition).

Following the acquisition of all pre-experimental details, pre-experimental EEG data with eyes open were concurrently collected for six minutes utilizing a 4-channel headband (four channels: TP9, TP10, AF7, and AF8), as illustrated in Figure 1. Subsequently, participants donned a VR headset in conjunction with a 4-channel headband to facilitate the collection of EEG data while driving.

Subsequently, participants were instructed to operate a vehicle under one of the four randomly assigned conditions depicted in Figure 2. The perspective is from the driver's seat, featuring a movable steering wheel and unobstructed views of the surroundings, simulating the experience of operating a vehicle. The landslide is observable and transpired in front of the vehicle. EEG data, positional data, and collision data from the participants were collected during the experiment, followed by a post-experience assessment utilizing questionnaires.

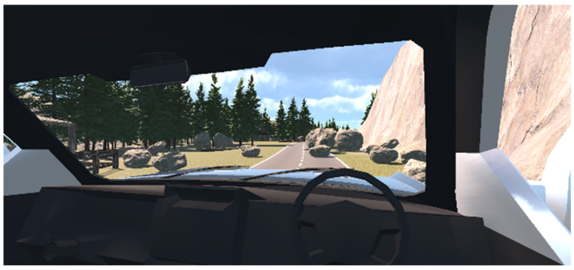

Figure 2: Participant’s point of view in Day condition.

The gathered data was processed using a number of methods. Python was used to process the EEG data for the pre-experimental and collision-area segments in order to calculate the Alpha/Theta, Alpha/Gamma, and Beta/Gamma measures. In order to determine the Euclidean distance, the number of collisions, and the velocity around the collisions, position and collision data are also processed using a Python script. Two-way ANOVAs were used on all behavioral and EEG measures to examine the effects of various between-subject training conditions.

5 RESULTS

5.1 Behavioral Measures

5.1.1 Ed Around Collision

ED around collisions was higher in high-probability scenarios (M = 219.75; SE = 26.50) than in low-probability ones (M = 82.16; SE = 26.85; $F(1, 75) = 13.30$, $p < 0.001$, $\eta p^2 = 0.15$; Figure 3). This indicates greater spatial navigation variation under higher collision risks. Lighting conditions (Day: M = 134.36; Night: M = 167.55) had no significant effect ($F(1, 75) = 0.51$, $p = 0.48$, $\eta p^2 = 0.01$). There was no significant interaction between landslide probability and lighting (High Probability - Day: Mean = 220.91; SE = 37.15, High Probability - Night: Mean = 218.59; SE = 37.13; Low Probability - Day: Mean = 47.81; SE = 37.15, Low Probability - Night: Mean = 116.50; SE = 37.13) ($F(1, 75) = 1.51$, $p = 0.22$, $\eta p^2 = 0.02$).

5.1.2 Number of Collisions

Collisions were more frequent in high-probability scenarios (M = 4.05; SE = 0.57) than in low-probability ones (M = 0.62; SE = 0.57; $F(1, 75) = 18.17$, $p < 0.05$, $\eta p^2 = 0.20$; Figure 3). This result indicates that if participants thought there was a greater chance of landslides, they were more likely to collide with falling rocks. Collisions were unaffected by lighting (Day: M = 2.45; Night: M = 2.22; $F(1, 75) = 0.51$, $p = 0.48$, $\eta p^2 = 0.00$) or probability-lighting interactions. (High Probability - Day: Mean = 4.62; SE = 0.81, High Probability - Night: Mean = 3.48; SE = 0.81; Low Probability - Day: Mean = 0.28; SE = 0.81, Low Probability - Night: Mean = 0.96; SE = 0.81) ($F(1, 75) = 1.51$, $p = 0.22$, $\eta p^2 = 0.00$).

5.1.3 Velocity Around Collision

Collision velocity was higher in high-probability scenarios (M = 411.67; SE = 52.57) than in low-probability ones (M = 109.94; SE = 53.26; $F(1, 75) = 16.26$, $p < 0.001$, $\eta p^2 = 0.18$; Figure 3). The results indicate that when participants were in more hazardous situations and faced collisions, they reacted faster, probably as a reflex to avoid the obstacles. Both lighting conditions had no significant effect on collision velocity (Day: M = 265.80; Night: M = 255.81; $F(1, 75) = 0.22$, $p = 0.64$, $\eta p^2 = 0.03$). Additionally, the interaction between landslide probability and lighting conditions was also not significant (High Probability - Day: Mean = 413.08; SE = 75.98, High Probability - Night: Mean = 410.25; SE = 75.98; Low Probability - Day: Mean = 118.53; SE = 75.98, Low Probability - Night: Mean = 101.36; SE = 75.98) ($F(1, 75) = 2.20$, $p = 0.14$, $\eta p^2 = 0.03$).

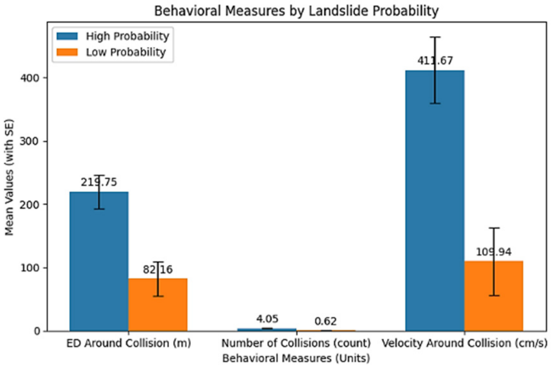

Figure 3: Graph of the three behavioral measures.

Three behavioral metrics are displayed in Figure 3: the Euclidean Distance (ED) around collision, the frequency of collisions, and the velocity around collision. The mean values (along with standard deviations) of these three metrics are displayed in the bar chart for both high and low landslide likelihood scenarios. The results showed that people displayed significantly higher ED around collisions, more collisions, and increased velocity around collisions in high-probability scenarios compared to low-probability scenarios. This suggests that participants were more likely to navigate erratically, collide with barriers, and move more quickly when they perceived a greater risk of landslides.

5.2 EEG Measures

5.2.1 Alpha/Theta

The landslide probability had a significant impact on the Alpha/Theta ratio. High-probability scenarios had higher ratios (Mean = 2.69; SE = 0.43) compared to low-probability scenarios (Mean = 1.37; SE = 0.43) (see Figure 4; $F(1, 76) = 4.62$, $p < 0.05$, $\eta p^2 = 0.56$). Participants' perception of a greater risk of landslides was associated with increased cognitive engagement and decreased relaxation. There was no significant effect of lighting conditions on the Alpha/Theta ratio ($F(1, 76) = 2.38$, $p = 0.13$, $\eta p^2 = 0.03$), suggesting that the day or night setting did not have a significant impact on Alpha/Theta ratio. In addition, the interaction effect between the probability of landslides and lighting conditions was not significant (High Probability - Day: Mean = 3.70; SE = 0.61, High Probability - Night: Mean = 1.68; SE = 0.61; Low Probability - Day: Mean = 1.31; SE = 0.61, Low Probability - Night: Mean = 1.42; SE = 0.61) ($F(1, 76) = 2.99$, $p = 0.09$, $\eta p^2 = 0.04$).

5.2.2 Alpha/Gamma

There were higher Alpha/Gamma ratios seen in high-probability scenarios (Mean = 1.91; SE = 0.14) than in low-probability scenarios (Mean = 0.97; SE = 0.14) (see Figure 4; $F(1, 76) = 22.25$, $p < 0.001$, $\eta p^2 = 0.23$). The results imply a higher level of focus, attention, and cognitive processing in reaction to more dangerous conditions. The primary impact of lighting conditions on the Alpha/Gamma ratio was found to be insignificant (Day: Mean = 1.68; SE = 0.14, Night: Mean = 1.20; SE = 0.14) ($F(1, 76) = 3.00$, $p = 0.09$, $\eta p^2 = 0.04$). There was also no significant interaction effect between landslide probability and lighting conditions (High Probability - Day: Mean = 2.37; SE = 0.20, High Probability - Night: Mean = 1.45; SE = 0.20; Low Probability - Day: Mean = 0.99; SE = 0.20, Low Probability - Night: Mean = 0.96; SE = 0.20) ($F(1, 76) = 2.25$, $p = 0.14$, $\eta p^2 = 0.03$).

5.2.3 Beta/Gamma

The main impact of landslide probability on the Beta/Gamma ratio was significant, where high-probability scenarios had higher ratios (Mean = 1.36; SE = 0.06) compared to low-probability scenarios (Mean = 0.85; SE = 0.06) (see Figure 4; $F(1, 76) = 31.05$, $p < 0.001$, $\eta p^2 = 0.29$). This implies a rise in cognitive workload and stress as a response to a higher perceived risk. The main impact of lighting conditions on the Beta/Gamma ratio was found to be insignificant (Day: Mean = 1.11; SE = 0.06, Night: Mean = 1.10; SE = 0.06) ($F(1, 76) = 0.16$, $p = 0.70$, $\eta p^2 = 0.00$). Lastly, there was also no significant interaction effect between landslide probability and lighting conditions (High Probability - Day: Mean = 1.36; SE = 0.08, High Probability - Night: Mean = 1.36; SE = 0.08; Low Probability - Day: Mean = 0.87; SE = 0.08, Low Probability - Night: Mean = 0.83; SE = 0.08) ($F(1, 76) = 0.49$, $p = 0.49$, $\eta p^2 = 0.01$).

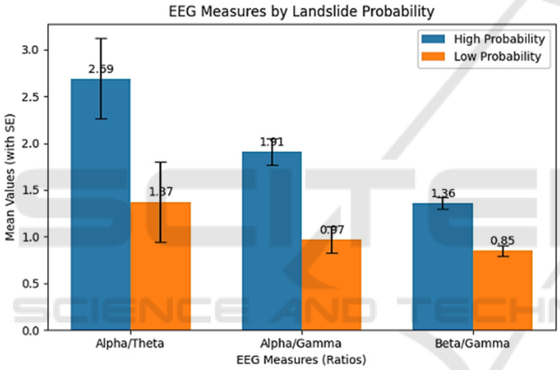

Figure 4: Graph of the three EEG measures.

The three EEG measures—Alpha/Theta, Alpha/Gamma, and Beta/Gamma ratios—mean values (with standard errors) were also compared as shown in Figure 4 for both high and low landslide probability scenarios. The findings show that in high-probability scenarios, all three ratios were considerably higher, suggesting higher levels of stress, focused attention, and cognitive involvement. This suggests that when individuals believed that there was a larger chance of landslides, they felt more stressed and under cognitive stress.

6 CONCLUSIONS

The study's findings provide intriguing new insights into how people respond to varying degrees of danger in landslide simulations, both behaviorally and neurophysiologically. The findings suggest that perceived risk, rather than ambient lighting conditions, is the primary factor influencing participants' cognitive and physiological responses.

6.1 Behavioral Responses to Perceived Risk

High-probability scenarios increased participants' course deviations, as shown by the rise in ED around crashes. This suggests cautious yet erratic navigation under pressure. Increased accidents suggest perceived threats led to more mistakes, aligning with higher stress and cognitive load.

High-risk conditions also saw increased crash velocities. According to this, Participants may have reflexively increased speed to evade perceived danger. However, higher speeds likely reduced control, leading to more crashes. Since lighting conditions did not significantly alter any of these behavioral measures, it is further evidence that perceived danger level—rather than visibility—was the primary factor influencing participants' behaviors.

6.2 Neurophysiology of Stress and Cognitive Engagement

These findings from behavior are supported by neurophysiological evidence. In high-probability circumstances, the Alpha/Theta ratio significantly increases, indicating increased cognitive involvement and attention. In order to prepare for the impending threat, participants were probably less at ease and more mentally concentrated. This fits with the observed propensity of behavior to increase velocity and diverge more from the route surrounding collisions.

A state of concentrated attention and cognitive processing is reflected in the Alpha/Gamma ratio, which also rose in high-risk circumstances. Not only were participants eager, but they were also focusing their mental energies on comprehending the intricate and ever-changing simulation environment. Although this enhanced amount of cognitive processing was required to navigate the dangerous environment, it's possible that it increased the number of crashes because it put more strain on participants' minds than they could handle.

In high-probability situations, there was a substantial increase in the Beta/Gamma ratio, a measure of cognitive strain and stress. This result emphasizes the elevated psychological stress that participants felt in reaction to the anticipated landslide danger. The observed behavioral consequences can be explained by the individuals' reduced capacity to conduct precise, controlled moves due to higher stress levels. Once more, this EEG evidence does not show a substantial effect from lighting conditions, indicating that perceived danger was the only factor influencing cognitive and emotional states.

6.3 Consequences of VR-Based Emergency Education

These results have major implications for VR-based disaster training design and implementation. Perceived risk strongly affects tension, cognitive engagement, and attention, as per the study. VR training simulations should prioritize realistic risk scenarios to evoke authentic cognitive and emotional responses.

We would project that the total cost of implementing VR-based training or education would not exceed £2000 (roughly ₹200000 INR). A performance desktop computer, a steering wheel with pedals, a virtual reality headset, and a multi-channel EEG band (for gathering EEG data) make up the majority of the hardware in a lab room that can accommodate all of this. If we were to train 80 participants, we would only need to spend 25 pounds per person, which could be as little as 2 pounds per person if there were 1000 participants. Mock drills involving real vehicles and controlled rockfall on such a large scale, in a large environmental setting, would be more costly in real life.

Furthermore, the findings imply that although greater cognitive involvement and processing help individuals become more adept at navigating dangerous situations, these advantages need to be counterbalanced by techniques for handling the stress and cognitive effort that come with it. VR disaster training programs may be more successful if they include instruction on stress management strategies, making decisions under duress, and building cognitive resilience.

6.4 Limitations and Prospects for Further Study

Although the study offers insightful information, there are several drawbacks. To improve the simulation's ecological validity, other environmental factors that are frequently connected to landslide-prone places, including rain, fog, or thunderstorms, might be added. Subsequent investigations may examine the impact of these supplementary environmental elements on the behavior and cognitive reactions of participants.

Furthermore, the findings' generalizability could be improved by increasing the sample's relative homogeneity. Thus, including a wider variety of backgrounds in the participant pool in the future may yield more complex insights and improve the robustness of the findings.

To obtain a more thorough knowledge of how various characteristics of physiological stress interact with behavioral outcomes in high-risk circumstances, future studies might also include additional physiological measurements, such as blood pressure, heart rate variability (HRV), and blood oxygen levels, along with neurofeedback. While the current study provides separate analyses of behavioral and EEG measures, future work may aim to establish integral analyses by correlating EEG metrics directly with behavioral outcomes. Specifically, metrics such as the Alpha/Theta and Beta/Gamma ratios, which indicate stress and cognitive engagement, can be examined in relation to behavioral markers like Euclidean distance and collision frequency. This approach would offer a deeper understanding of how cognitive and emotional states influence real-time decision-making and performance in high-risk virtual environments.

6.5 Conclusions

This study demonstrates that perceived danger, not lighting, drives behavioral and neurophysiological responses in simulated landslides. By simulating actual crises and evoking genuine emotional and cognitive responses, virtual reality (VR) holds promise as a disaster training tool. Future research may also provide more thorough insights into participants' preparedness and reactions in such circumstances by integrating behavioral and EEG data. Integrating stress and cognitive effort management can enhance VR-based disaster training programs.

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