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RESTORATIVE SOUNDSCAPE DESIGN FOR RESTING PLACES IN PURPOSE-BUILT VEHICLES: ENHANCING RELAXATION AND WELL-BEING THROUGH AUDIO-VISUAL ENVIRONMENTS

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ABSTRACT

With the advancement of autonomous driving technology, vehicles are transforming from mere modes of transportation into multifunctional spaces that support a variety of in-cabin activities. This study focuses on the design of restorative soundscapes for resting places in Purpose-Built Vehicles (PBVs), aiming to enhance user relaxation and well-being. We investigated the effects of auditory and visual stimuli on stress reduction and relaxation, using heart rate variability (HRV) as a physiological indicator to quantify the restorative potential of in-vehicle environments. Results demonstrated that personalized soundscapes incorporating natural elements significantly reduced stress levels and promoted relaxation. Furthermore, the effectiveness of these environments varied depending on vehicle frame design and the degree of external visibility. This study highlights the importance of soundscape-based UX design for PBV resting spaces and proposes practical design guidelines to improve in-cabin comfort, health, and well-being in future mobility systems.

Keywords: Indoor Soundscape, Autonomous Vehicle (AV), Resting Place, Human Perception, Psycho-psychacoustics.

1. INTRODUCTION

The concept of in-cabin UX design for resting places has gained relevance with the rise of autonomous vehicles, which are evolving into multifunctional environments. As vehicle interiors begin to support activities beyond driving—such as rest, work, and entertainment—dedicated spaces for relaxation and psychological recovery have become increasingly important, especially within Purpose-Built Vehicles (PBVs).

A key element in shaping such restorative environments is soundscape design, which plays a critical role in enhancing passenger comfort and promoting a sense of well-being. Tailored auditory environments, when effectively integrated with the vehicle's visual and spatial design, can support psychological calmness and reduce stress. Therefore, this study explores the fundamental soundscape characteristics required for UX design in autonomous vehicles, focusing on three core categories that contribute to a restorative in-cabin experience. Firstly, attributes such as 'familiarity' and 'calmness' are essential for promoting comfort within the vehicle environment [1,2]. These qualities foster a sense of psychological stability and encourage users to remain in the space for longer periods, enhancing their engagement and overall satisfaction. Secondly, the presence of 'natural' elements [2,3] and 'natural vision' elements [4] are critical content features for simulating restorative environments within enclosed vehicle cabins. Incorporating visual and auditory components inspired by nature has been shown to reduce stress and facilitate emotional recovery, helping passengers experience a greater sense of tranquility. Thirdly, characteristics such as 'not irregular' [1], 'low eventfulness'

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[5], and ‘low noisiness’ [2] represent design principles particularly relevant to artificial or engineered environments like vehicle interiors. These features contribute to creating a controlled, low-stimulation soundscape that minimizes stress and supports users’ restorative experiences even in non-natural, in-cabin settings.

Building upon these three core conditions, the present study proposes a soundscape design strategy for the interior UX of PBVs that aims to maximize stress relief and psychological restoration for passengers. By integrating these design principles into the in-cabin environment, we seek to develop a framework that enhances user well-being and supports the creation of truly restorative mobility experiences.

2. METHOD

To assess the effectiveness of UX design for in-cabin resting places, a two-phase immersive VR experiment was conducted with 39 participants. VR content was presented using a 360-degree headset (VIVE Pro 2) and noise-isolating headphones to enhance immersion and control auditory input. In Phase 1 (Case 1), participants were exposed to a stress-inducing virtual office environment featuring unpleasant urban visuals and negative auditory stimuli, including emotionally negative speech (63 dBA) and background driving noise (47 dBA). Phase 2 (Case 2) simulated a restorative environment, where participants selected one of 23 relaxing panoramic VR scenes (e.g.,

water, forest, temple) and paired it with natural background sounds and one of ten music options, such as Korean traditional, classical, or ambient music. Driving noise was kept consistent (47 dBA) to simulate a personalized recovery experience.

During each experimental condition, physiological data were collected, focusing on HRV indicators such as heart rate (HR), total power (TP), LF/HF ratio, SDNN, RMSSD, and physiological stress index (PSI). After the VR sessions, participants completed psychological and perceptual questionnaires, including indoor soundscape evaluation (pleasantness and eventfulness), the Perceived Restorativeness Soundscape Scale (PRSS), and the Relaxation State Questionnaire (RSQ). In Case 2, the Design Quality Index (DQI) was additionally assessed. This comprehensive approach enabled a multi-dimensional evaluation of in-cabin UX design for stress reduction and recovery in autonomous vehicle resting spaces.

3. RESULT AND ANALYSIS

This study evaluated the stress-relieving effects of three virtual environments—Water + Sky, Forest, and Temple—using HRV, soundscape assessments, the RSQ, and PRSS. Water + Sky showed the strongest restorative response, with increased autonomic activity (SDNN) and reduced PSI. Temple showed a moderate effect with reduced heart rate, while Forest showed no significant HRV changes, and a slight increase in LF/HF ratio suggested mild sympathetic

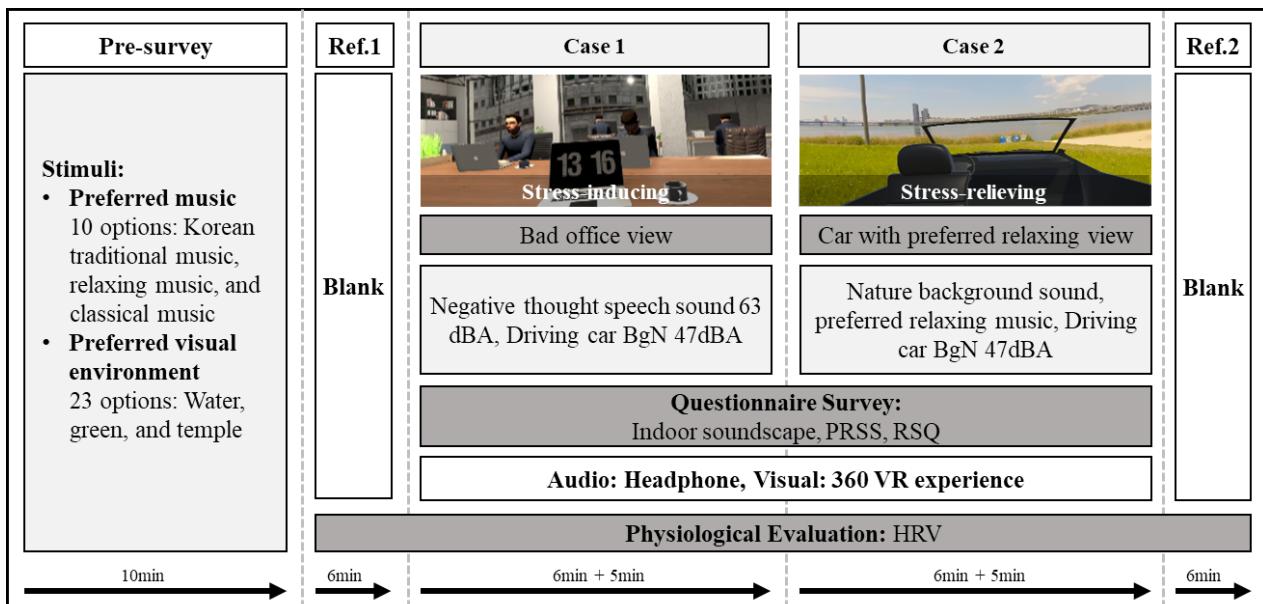


Figure 1. Experiment test procedure.





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activation. In perceived evaluations, Water + Sky increased comfort and aligned with HRV results. Forest enhanced engagement and enjoyment but lacked physiological support, revealing a gap between immersion and recovery. Temple also improved perceived comfort, consistent with reduced heart rate.

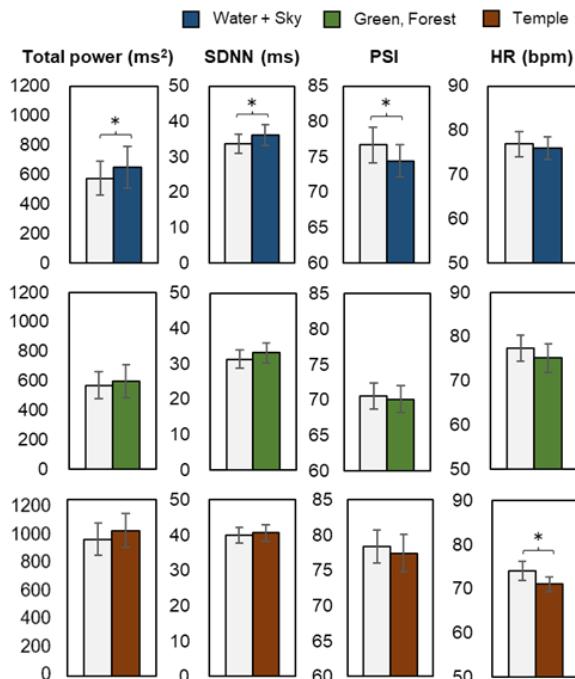


Figure 2. HRV responses on 3 types of soundscape environments.

According to the RSQ results, the Water + Sky environment elicited the strongest subjective effects, including cardiovascular, muscular, and overall relaxation—contributing to a calm yet alert state. The Forest environment showed limited improvement, mainly in cardiovascular relaxation, while the Temple environment was associated with physical relaxation and drowsiness, suggesting its suitability as a sleep-oriented space. In the PRSS evaluation, Water + Sky again showed the most immersive and emotionally restorative effect. Forest was perceived as familiar and comfortable but lacked transformative qualities, resulting in limited physiological benefit. Temple was seen as structured and detached but valuable as a quiet, contemplative setting. Overall, Water + Sky proved most effective for stress relief and recovery, while Temple offered moderate effects and Forest provided subjective comfort with minimal physiological change.

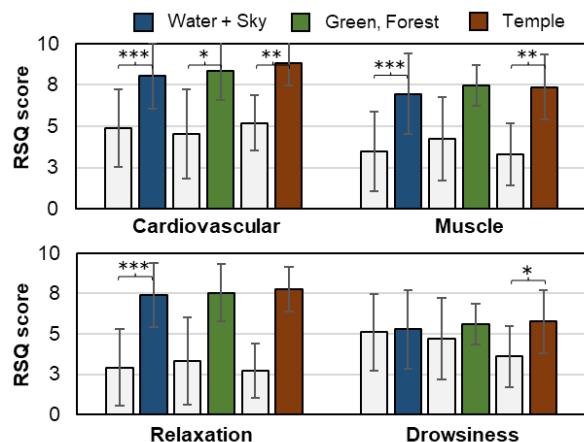


Figure 3. RSQ responses on 3 types of soundscape environments.

RSQ results showed that the Water + Sky environment provided the strongest subjective relaxation effects—cardiovascular, muscular, and overall—promoting a calm yet alert state. Forest showed partial improvement, mainly in cardiovascular relaxation, while Temple was linked to physical relaxation and drowsiness, suggesting a sleep-oriented function. In PRSS evaluations, Water + Sky again offered the most immersive and emotionally restorative experience. Forest was seen as familiar and comfortable but lacked transformative qualities, limiting its physiological impact. Temple appeared structured and emotionally detached but was valued as a quiet, contemplative space. Overall, Water + Sky was the most effective for stress reduction and recovery. Temple showed moderate benefits, while Forest, though subjectively pleasant, provided minimal physiological restoration.

4. DISCUSSION

This study proposes the Integrated Passenger Well-Being Framework for designing resting places in PBVs. Centered on environmental design, human factors, and multisensory integration, the framework aims to enhance in-cabin well-being by reflecting the physiological and psychological responses observed in the experiment. The framework emphasizes acoustic environments (e.g., noise control), visual elements, and natural features as key design factors for effective rest spaces, enhancing user immersion, comfort, and stress reduction. It also highlights the value of ISO-based acoustic design and sound quality evaluation, which support objective assessment and are closely linked to environmental satisfaction and psychological restoration.





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Based on the findings, the framework illustrates how audio-visual environments influence user perception to enhance immersion and relaxation. It offers an integrated UX design approach that goes beyond aesthetics to support stress reduction and psychological recovery. This framework can inform future PBV designs with practical guidelines for promoting user well-being (see Figure 4).

5. SUMMARY

Among the three environments, Water + Sky proved most effective for physiological recovery, subjective relaxation, and perceived restorativeness. Forest was rated positively in subjective terms but showed limited physiological effects. Temple provided moderate recovery and was better suited for quiet, meditative experiences. Based on these restorative response patterns, the recommended user profiles for each environment are as follows:

- 1) Water + Sky: Individuals experiencing mental overload or high levels of stress
- 2) Forest: Emotionally fatigued individuals or those with an introverted disposition who prefer natural settings
- 3) Temple: Individuals with strong spiritual inclinations or empathic personalities experiencing deep fatigue

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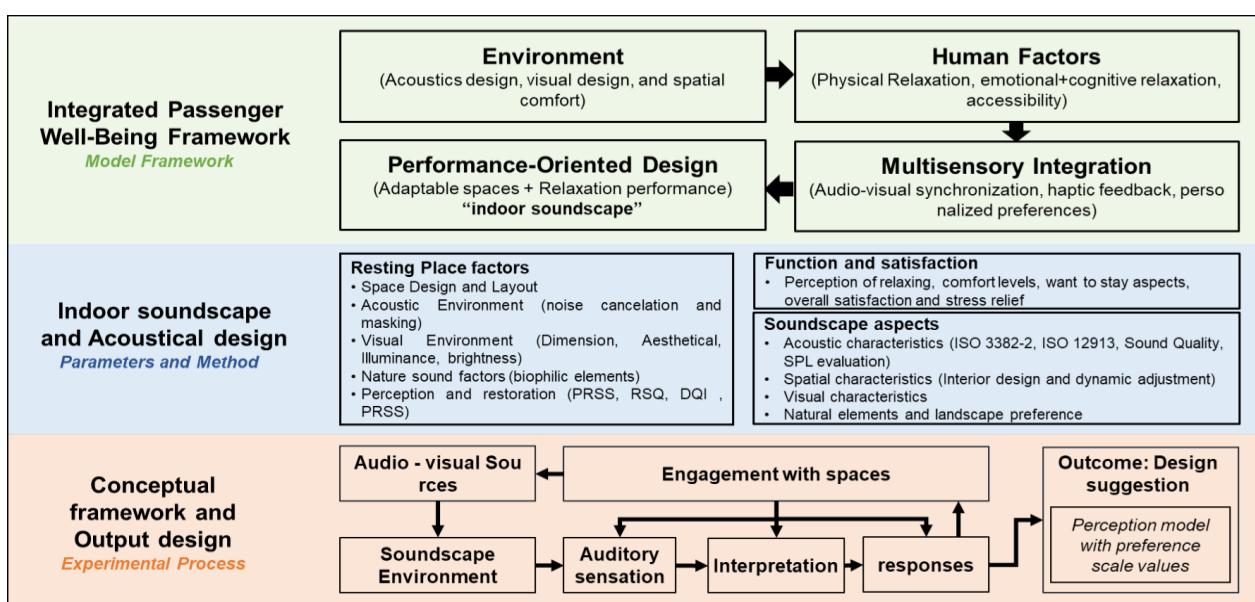


Figure 4. Integrated Passenger Well-Being Framework and Conceptual Framework for In-Cabin UX Design.



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