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A bio-monitoring tool for quantifying the effect of sound -and landscape on mental restoration in real nature and in virtual reality

Jolien Vonck[1], Jorg De Winne[1,*], Ehsan Eqlimi[1,*], Dick Botteldooren[1]

[1]WAVES research group, Department of Information Technology,
Ghent University, Ghent, Belgium

*{jorg.dewinne, ehsan.eqlimi}@ugent.be

Abstract
Mental restoration after a stressful situation or a demanding activity is important for health and well-being. This restoration can be found in a variety of ways and is rather personal. Research has already shown that experiencing nature is a factor that promotes mental restoration in most persons. However, quantifying this effect of the (sound) environment is challenging. This work explored the use of virtual reality (VR) to faithfully reproduce the landscape and soundscape of environments that are perceived as either restorative or non-restorative. Biomarkers related to stress were measured by means of electroencephalography (EEG), functional near-infrared spectroscopy (fNIRS) and galvanic skin response (GSR). In a second phase, the setup was moved outside the lab to capture the effect of real nature. Skin conductance results show that there is an overall positive effect of restorative environments on mental restoration. The cognitive effect on the other hand was not significant in the lab experiment, but was much stronger in real nature. Several explanations and improvements are offered to overcome this ambiguity.

Keywords: EEG, fNIRS, Galvanic Skin Response, Virtual Reality, Mental Restoration.

1 Introduction

Mental distress during the COVID-19 pandemic dramatically increased the rates of mental illness and substance use that existed prior to the current crisis. Nowadays, nearly one billion people suffer from a stress related disorder, including depression and anxiety [1]. In order to keep stress at bay and enhance the quality and longevity of life, it is vital to relieve stress easy and effectively. Current treatment methods are usually focused on coping strategies and counselling, as health physiology generally disregards the effect of the physical environment. Nevertheless, there is increasing evidence which suggests that the exposure to natural environments is beneficial for mental health and well-being. Restoration can be defined as the process of recovery from a depleted psychological, physiological or social resource [2]. It is key in stress relief, and associated with the restorative qualities of surroundings. There are currently two theories that dominate literature on restorative environments, being the attention restoration theory (ART) and the stress recovery theory (SRT). ART focuses on attention fatigue, and assumes that attention is needed to overcome the effects of constant stimulation in urban environments [3]. SRT, on the contrary, proposes a psycho-evolutionary framework where the restorative response to nature is an ancient evolved adaptive threat [4]. Both theories highlight the importance of natural environments in reducing stress and improving overall cognition and physiological health. This research hypothesizes that mental restoration happens more quickly and thoroughly in restorative environments in comparison to non-restorative settings. The aim of this work is to provide a bio-monitoring tool which facilitates quantifying the effect of sound –and landscape on mental restoration, and can be used to compare environments, based on their restorative or non-restorative qualities. If successful, this tool can aid research on the link between surroundings and mental health, and eventually be used to optimize healthy city design, especially in highly urbanized areas.

2 Experimental design background

2.1. Stress induction

In order to conduct a research study on mental restoration, it is necessary to induce a state of mental stress in the desired subject, at the right moment of time. This stress induction needs to be enough to provoke a stress response and observe the intended effects, while still adhering to ethical standards. Traditional protocols to induce moderate stress levels include the Cold Pressor test, which involves the immersion of the non-dominant hand in an ice-cold water bath [5], and the Trier Social Stress test, where participants need to take over the role of a job applicant [6]. Other methods to activate the stress response are based on the execution of specific tasks, such as the Stroop Color Word test (SCWT). During this individual test, a color word is presented on a screen and the participant needs to identify the font color of that word. A new color word will appear every second, so a quick response is required [7]. Another stress inducing test is the Hamilton Letter Transformation test (HLTT). The participant is presented with 1 to 4 letters and a number, for example, 'A T K +2'. The goal is to transform the given letters by moving a given distance upwards through the alphabet [8]. Hence, the answer to this specific example is 'C V M'. Technology is emerging at a fast pace, which opens possibilities to increase the interactivity and realism in research settings. Several studies confirm the potential of virtual reality (VR) [9], and augmented reality [10] in stress inducing protocols. Also, the use of video games is explored [11].

2.2. Selection of environments

To develop a bio-monitoring tool for assessing mental restoration, it is needed to select several environments that will be perceived as either restorative or non-restorative. Because the difference is not black and white, it is vital to carefully select the stimuli, and take into account the broader context and associative factors. SRT claims that restoration is intimately tied to underlying human needs and is expected to be greater for locations that promote thriving and effective functioning, crucial for survival [4]. Hence, to be restorative, an environment needs to feel familiar and coherent in order to avoid confusion and discomfort [3]. According to the ART, additional conditions are the sense of being away, compatibility and extent [12].

2.3. Stress assessment

Stress, and in like manner mental restoration, can be monitored objectively, as well as subjectively. As the stress response is characterized by a homeostatic imbalance, it can be assessed by measuring biochemical markers such as brain oxygenation by means of fNIRS. Another possibility is to check physiological changes, as the stress response will influence the galvanic skin conductivity and neural activity. The former can be obtained with the use of a GSR sensor, while the latter can be measured by means of EEG. Psychological alterations, like an increase in irritability, frustration or helplessness, are often evaluated by self-report questionnaires and mood charts. Despite accurate and reliable measurement techniques, it remains challenging to assess stress levels, as stress is a highly individualistic experience, and is perceived and coped with differently among people [13].

3 Materials and methods

Potential biomarkers for mental restoration, including alpha and beta band power, brain oxygenation and galvanic skin conductivity, were validated by exposing participants to a challenging cognitive task and comparing the response during a successive relaxation period in which participants were embedded in distinct environments. In a laboratory phase, landscapes and soundscapes of environments with mainly restorative and non-restorative features were faithfully reproduced using VR technology. In a second phase, as a proof of concept, part of the setup was moved to real-world natural and urban surroundings to explore their restorative potential.

3.1. Participants

A total of 26 healthy subjects (17 female, 9 male, mean age 27 ± 13 years) were recruited to perform the laboratory experiments. Based on their responsiveness to stress induction, their willingness to participate a second time and the distance of commute to the experimental locations in the midst of COVID restrictions, 6 participants (5 female, 1 male, mean age 31 ± 15 years) were re-invited for the real-world experiment. Participants had a minimum age of 18 years old and had self-reported general good health, normal hearing and normal or corrected to normal vision. Written informed consent was obtained from all of them prior to participation. The study was approved by the ethics committee of the faculty of arts and philosophy of Ghent university. As economic compensation for their participation, all subjects received a gift voucher worth €10. No additional compensation was provided for participation in the real-world experiment.

3.2. Experimental protocol

The experimental task was designed to monitor the effect of the environment on mental restoration. The task comprised four successive blocks, each divided into three main parts: a stress induction phase of 4 min, a restoration phase of 9 min 30 s, and a mood chart (Figure 1). The stress induction phase was based on a combination of the Stroop and the Hamilton test. Tests were alternated as in order to abate habituation. To further induce stress levels, a challenging time limit was added. During the restoration phase, the participants were allowed to relax while watching fragments of deliberately selected environments. Objective quantification of the cognitive restoration process was achieved by including four standard arithmetic tasks of 30 s, as analyzing the measurements during these tasks reduces the environmental bias.

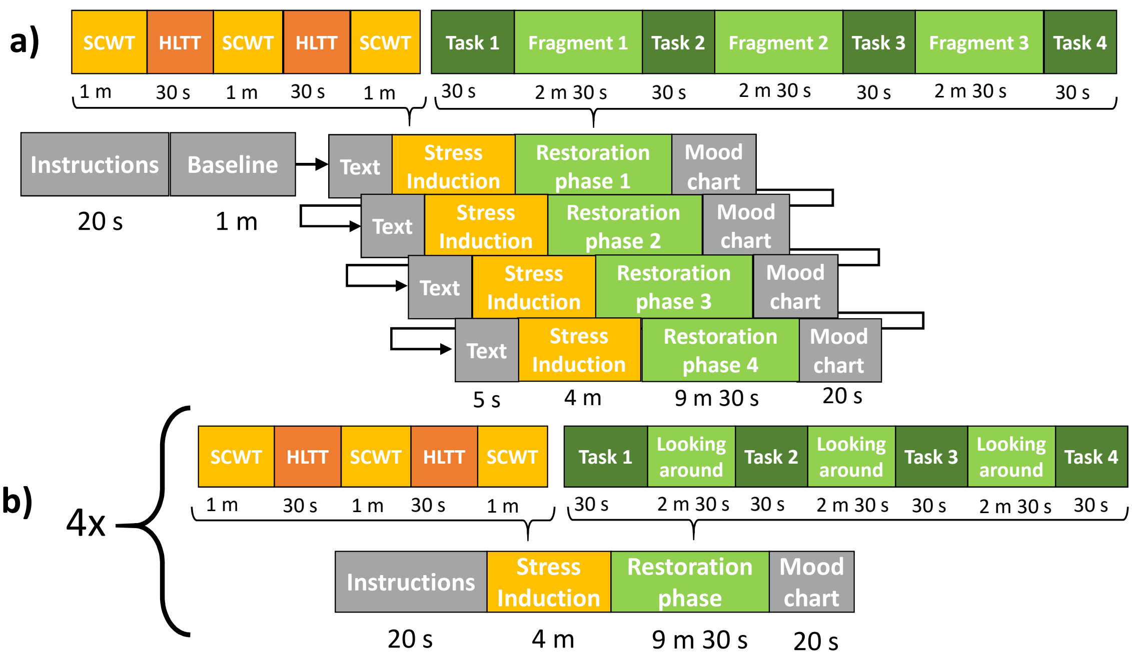

Figure 1: a) Block design of the experimental task performed in the laboratory. b) Block design of the experimental task performed in different real-life natural and urban environments.

To allow the comparison of mental restoration in different settings, two blocks contained fragments of a restorative environment, while the two remaining blocks included the non-restorative fragments. The order of blocks was counterbalanced across participants. Mood charts were included at the end of each block. Participants got 20 s to describe their mood by choosing three out of six given emoji's, starting with the most appropriate one. Additionally, participants were asked to fill in a final questionnaire about their perception of the presented environments. As the immersion of an individual with the environment is an incredibly important component of the interaction in terms of mental restoration, the experimental task was shown through VR. To improve the VR experience, participants were seated on a comfortable office chair, allowing a 360° rotation. Simultaneous frontal and occipital EEG, frontal fNIRS and GSR recordings were performed. The whole setup was located in a dark and sound-attenuated room.

The proof-of-concept experiments were performed on a smaller scale with the main purpose of verifying whether the bio-monitoring tool has practical potential in real-world environments. In order to assure a viable comparison of the results obtained in the laboratory and those collected in the real-world surroundings, the design of the experimental task remained as unchanged as possible. Participants were transported to three or four different locations, where they performed the previously described stress induction part in VR. During the restoration phase, the headset was carefully taken off, and they were allowed to look at the real-world surroundings during the next 9 min 30 s. Again, a mood chart was included at the end of each restoration phase. During the proof-of-concept experiments, brain oxygenation and galvanic skin conductance were measured by means of a portable fNIRS device and a GSR sensor. The used EEG equipment was not suitable for mobile recordings, thus EEG measurements were omitted.

3.3. Equipments and data recording

Nine-channel EEG data were recorded using an ActiveTwo amplifier (BioSemi, 2048 Hz sampling rate) and ActiView recording software. The nine active electrodes were located, according to 10−20 electrode placement, at seven frontal (FP1, FP2, Fz, F3, F4, F7, F8) and two occipital (O1, O2) electrodes. The reference electrodes EXG1 and EXG2 were positioned on the left and right earlobe. To ensure equivalent placement of the EEG cap, the vertex electrode position on the cap (Cz) was placed at 50% of the distance between inion and nasion and between left and right ear lobes. A low impedance and highly conductive electrode gel (SignaGel, Parker laboratories Inc) was applied to keep all electrode impedances below $30k\omega$. To measure the raw fNIRS data, a NIRSport 2 device (NIRx, 10.17 Hz sampling rate) and the Aurora 2020.7 acquisition software were used. The system employs two wavelengths, 760 nm for HbR and 850 nm for HbO_2. According to the $10-20$ system, eight sources (FPz, AF3, AF4, AFz, F1, F2, F5, F6) and eight detectors (AFP1, AFp2, AF7, AF8, AFF1h, AFF2h, AFF5h, AFF6h) were positioned on the prefrontal cortex. Sources and detectors were integrated together with the EEG electrodes in one single NIRx cap. Together they formed 21 source-detector pairs or channels (Figure 2).

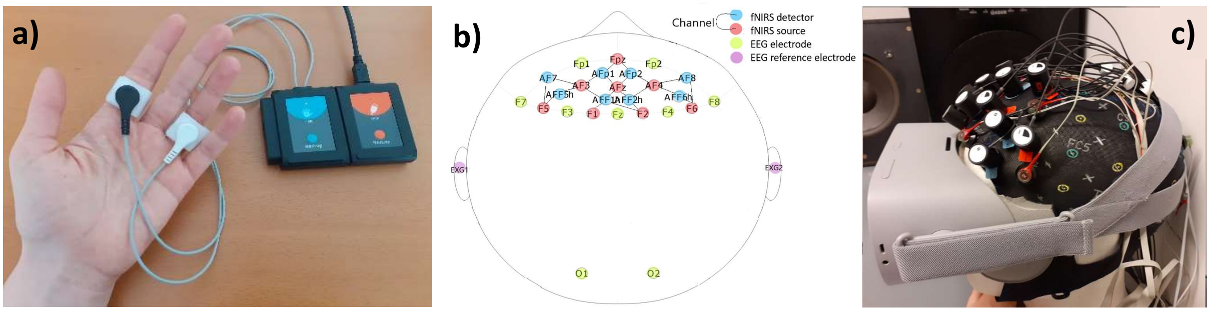

Figure 2: a) GSR sensor connected to ring –and index finger. b) Combined EEG and fNIRS electrode placement. c) Combined setup with EEG and fNIRS integrated in a single cap and adjusted VR glasses.

Skin conductivity was measured with a GSR logger sensor (NeuLog NUL-217, 2 Hz sampling rate), connected to the ring –and index finger. The experimental task was presented using an Oculus Go VR headset. The goggles were slightly adapted to accommodate all electrodes without unnecessary pressure. Four fragments (two restorative, two non-restorative) were selected from the Urban Soundscapes of the World database [14]. More details can be found in Table 1. Previews are available through the database website [14]. Four real-life locations were selected for the second experiment. Their characteristics are summarized in Table 2.

Table 1: Overview and description of the VR fragments used during the laboratory experiments. Fragment codes are consistent with numbering in the Urban Soundscapes of the World database [14]

Fragment	Location	Setting	Auditory and visual features
R0025	Tianjin (CH), Xinkai Lake (NKU Campus)	Restorative	Serene lake, few buildings, rustling leaves
R0126	Vilnius (LT), Uzupis Art Incubator	Restorative	Picturesque village at riverbank, open-air art gallery, running water, rustling leaves, some hikers
R0042	Hong Kong, Nelson Street	Non-restorative	Crowded noisy street, passing traffic, honking cars, talking people, flashing traffic lights
R0047	Hong Kong, Peking Road	Non-restorative	Crowded noisy street, passing traffic, honking cars, talking people, flashing traffic lights

Table 2: Overview and description of the selected locations during the real-life experiments.

Fragment description (visual features)	Setting	Auditory features
Panoramic view of rural surroundings	Predominantly restorative	Sound of the wind, rustling leaves, chirping birds
Peaceful garden scene between trees and hedge, next to exterior house wall.	Predominantly restorative	Sound of the wind, rustling leaves, chirping birds
Parking lot next to busy roundabout	Predominantly non-restorative	Busy traffic noise
Secondary street across construction site	Predominantly non-restorative	Driving cars, jackhammer, construction, cars honking

3.4. Data preprocessing and analysis

Raw EEG and fNIRS data were pre-processed in MATLAB (version R2019b), using the EEGLAB [15] and NIRS Brain AnalyzIR [16] toolbox. For the pre-processed EEG signals, the average frontal and occipital alpha and beta powers for each arithmetic task were computed over the interval [5 s, 15 s] after task onset. Furthermore, z-scores were calculated to account for individual differences in alpha and beta activity. The same time window was applied for computing the mean normalized HbO_2 concentration change in channel 19 for each arithmetic task. Moreover, the mean skin conductivity was calculated over the total duration of the arithmetic tasks. Next, mental restoration was quantified by computing the changes in biomarker signals between successive arithmetic tasks within the same environmental blocks. Additionally, the total mental restoration within each block was assessed by calculating the difference between the first and the last task within that block. Moreover, mood chart data was analyzed by computing the weighted score of the moods for each environmental analysis block. Statistical analyses, including pairwise t-tests with Bonferroni correction, were done in R (version 4.0.4). Additionally, the potential of the measured features to be used as biomarkers in a bio-monitoring tool was explored through a generalization of multiple linear regression and receiver operating characteristic (ROC) curve analysis.

4 Results

4.1. Laboratory experiments

From the pool of 26 participants, some were removed from the analysis due to suffering motion sickness caused by the VR application, poor responsiveness to the stress inducing part, technical issues, or noise contaminated signals.

EEG—For the combined sample of 17 participants there was not a statistically significant ($p > 0.1$) difference of z-scored alpha and beta band power between successive arithmetic tasks, for both the restorative and the non-restorative blocks. It was quite remarkable that the distributions of the frontal alpha power, the occipital alpha power, and the frontal beta power portrayed a similar trend: an increase in the first half of the restoration phase, followed by a decrease towards the end. Furthermore, the total mental restoration in the restorative and non-restorative blocks did not significantly differ.

fNIRS—Statistical analyses performed on the data of 21 participants revealed an increasing trend of averaged normalized change in HbO_2 concentration between successive tasks of the restorative and non-restorative blocks. Moreover, the total mental restoration in the restorative blocks was higher compared to the non-restorative ones. Notwithstanding, differences were not statistically significant.

GSR—The skin conductivity of the 22 analyzed participants showed a decreasing trend in both the restorative and the non-restorative restoration phases. Furthermore, the total decline over the entire restoration phase was higher in the restorative blocks. Nonetheless, no statistical significance was observed.

Mood chart—Results showed that the 22 included participants were significantly more frustrated ($p = 0.022$), less happy ($p = 0.0017$), and more stressed ($p = 0.038$) at the end of a non-restorative block compared to the end of a restorative block. Even though not significant, the average participant reported a slight increase in boredom, and a decrease in confidence and excitement at the end of the non-restorative blocks.

GLMM—Generalized linear mixed-effects models (GLMMs) were designed based on the computed total mental restoration datasets and included a personal random factor. The ROC curves of the different models are plotted in Figure 3 and the respective areas under the curve (AUC) are listed in the first row of Table 3. The subjective model based on the mood chart data performed better than the objective models in terms of the area under the ROC curve. Moreover, the objective models had a rather poor performance.

4.2. Real-life experiments (proof of concept)

The statistical analyses discussed in this section were performed on the data of 6 participants. Half of the performed experimental tasks were executed in an environment with predominantly non-restorative elements, while the other 10 trials were performed in a restorative environment. Due to technical issues, the fNIRS and GSR data of one experiment were omitted.

fNIRS—No statistical difference was observed when computing the pairwise comparisons between successive tasks of the non-restorative, as well as the restorative locations. Nevertheless, the total mental restoration was significantly ($p = 0.017$) higher in the restorative environments, with an increase in normalized HbO_2 concentration change of 2.61 ± 1.53 between the first and the last task, compared to a decrease of 0.534 ± 1.61 in the non-restorative settings.

GSR—No statistical significant difference was found between the skin conductance in successive tasks. However, the difference between the total mental restoration in the restorative and non-restorative environments was significant ($p = 0.1$). The total decrease in skin conductance in the restorative environments was $423 \pm 475\ nS$. For the non-restorative surroundings, the skin conductance increased with $117 \pm 347\ nS$ between the first and last task.

Mood chart— At the end of the experimental tasks executed in the restorative locations, participants were statistically more confident ($p = 0.027$) and less stressed ($p = 0.0021$) compared to the tasks performed in non-restorative environments. Despite the lack of statistical significance, participants felt more bored and happier, and less excited and frustrated in the restorative environments.

GLMM—The ROC curves of the different models are plotted in Figure 3 and the respective areas under the curve (AUC) are listed in the second row of Table 3. All GLMMs were designed with the computed average of the three restorative conditions and the average of the three non-restorative conditions. In terms of predictive ability, the GLMMs with the fNIRS data included clearly outperformed the subjective model with the three emoji's. Moreover, all models had a relatively good fit, compared to the laboratory GLMMs.

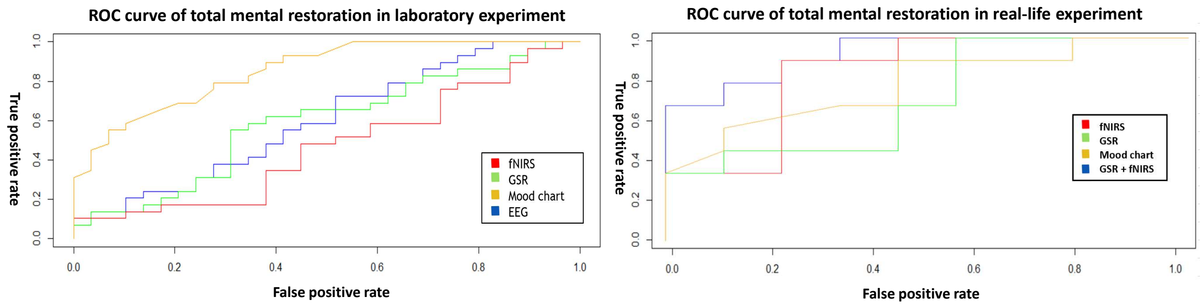

Figure 3: ROC curve visually comparing the models based on the fNIRS, GSR, EEG, and mood chart data computed to assess the total mental restoration in the restorative and non-restorative environments for the laboratory (left) and real-life (right) experiments.

Table 3: The AUC results using different models for the laboratory and real-world experiments. AUCs near to 1 denote the good models of separability between restorative and non-restorative environments.

Experiment type	EEG	fNIRS	GSR	fNIRS+GSR	Mood chart
Laboratory	0.6218	0.4696	0.5885	-	0.8549
Real-world	-	0.8271	0.7037	**0.9259**	0.7716

5 Discussion

EEG results are questionable, as literature reports that frontal beta power is usually negatively correlated with frontal alpha power when studying the stress response [17], which was not observed in this study. A possible explanation could be the very low signal-to-noise ratio due to movement artifacts.

The fNIRS and GSR measurements, on the other hand, showed results confirming the hypothesis that mental restoration happens faster and more thoroughly in restorative environments compared to non-restorative ones. Conforming to literature, an increase in normalized HbO_2 concentration change is positively correlated with increased mental restoration [17]. Furthermore, previous studies confirmed that a decrease in skin conductance is associated with a reduction in mental stress [18, 19]. Nevertheless, differences in the laboratory measurements of the objective biomarkers are not as clear as expected. As changes are more prominent in the proof-of-concept experiments, it is demonstrated that human behavior still differs between simulated and real-world environments. Real-life stressors are suspected to be much more intense than their virtual replicates. An additional element in favor of this assumption is social stress. In real-world settings, the presence of other people possibly increases stress levels in the participants, as they feel a little ashamed with the EEG, fNIRS and VR equipments on their head.

Moreover, it is important to be aware that the self-reported answers may be affected by a bias, induced from the participants' individual perceptions and social desirability. Laboratory findings of the mood chart analysis demonstrated that positive feelings were more present at the end of the restorative blocks. The non-restorative blocks were characterized by an increase in negative feelings. The results of the mood charts obtained during the proof-of-concept experiments had the increase in frustration and stress in the non-restorative environments in common with the laboratory experiments, but were also characterized by a higher level of excitement compared to the moods mentioned in the restorative surroundings. The restorative environments were more associated with boredom, confidence, and happiness. Some previous studies reported the correlation of stress and negative mood, but did not distinguish between specific moods [20, 21]. According to Kaplan's ART hard fascination is more likely to reduce boredom [12]. This can explain the increase in boredom in the real natural environments, and again confirms that the effect of the environments is more pronounced in real-world environments. When using the subjective models as a benchmark for the evaluation of the objective models, it is clear that the objective models from the laboratory experiments fail to accurately predict the character of the environment. The combination of GSR and fNIRS, on the other hand, is very promising as a bio-monitoring tool, and proves that the effect of the environment on mental restoration can be objectively assessed. Beyond any doubt, caution needs to be taken in generalizing the results from the small sample of subjects as few studies report that the stress response can be influenced by social characteristics including gender, age, income, ethnicity, and adverse childhood [22].

Results obtained from this study highlight that galvanic skin conductivity and brain oxygenation are suitable biomarkers for assessing the effect of environments on mental restoration. Future research should explore the predictive capability of EEG measurements in more detail. One of the most prominent improvements that can be considered is the use of more efficient and robust methods in both the preprocessing and analysis of EEG data. An experimental protocol that minimizes external and internal cerebral noise can be another improvement. Moreover, it is recommended to instruct the participants to limit head movements as much as possible during the arithmetic tasks. The use of portable EEG devices in outdoor settings may also be helpful in gaining more knowledge. Several commercial options already exist, but special care should always be taken to avoid extensive movement artifacts during analysis. Additionally, more research is needed to study the influence of social characteristics such as gender, age, income, ethnicity, and adverse childhood on the stress response. Some suggestions to improve the experimental protocol include the use of a VR headset with a higher resolution, compared to the basic version used in this research. Special attention should be paid to the selection of the virtual environments, and new ways should be explored to match these high-quality recordings with real-world settings. Future studies should also aim at focusing on the comparison of the different environments, instead of only labelling them as restorative or non-restorative.

6 Conclusion

The laboratory results of the z-scored alpha and beta band powers are contradicting, and not in line with studies supporting the detection of mental stress using EEG signals [17]. This is probably due to the low signal-to-noise ratio, mainly caused by movement artifacts. The physiological fNIRS and GSR measurements, on the other hand, prove that mental restoration can be objectively assessed. The obtained results confirm the hypothesis that mental restoration happens faster and more thoroughly in restorative environments compared to non-restorative settings. Even though differences are not statistically significant in the laboratory experiments, the effects of the surrounding on mental restoration are clearly visible during the proof-of-concept experiments. Measurements in real-world natural settings are characterized by substantially higher increases in HbO_2 concentration change compared to the urban surroundings. Furthermore, higher declines in galvanic skin conductivity are observed. ROC curve estimation reveals that a bio-monitoring tool based on the combination of fNIRS and GSR measurements is the most promising. Including simple subjective measures such as mood charts can be helpful to further increase the performance of the tool. Although VR experiments have tremendous potential, the results of this research demonstrate that human behavior still differs between simulated and real-world environments. Experimental findings suggest that real-world stimuli are much more intense than their virtual replicates. Hence, new ways need to be explored in order to improve the matching of virtual environments with real-world settings. This work also highlights the importance of portable measurement devices and employing the efficient and robust analyses for the EEG and fNIRS data in order to conduct field experiments.

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