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Comparing the restorative effects of urban with green spaces: a laboratory study in VR

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ABSTRACT

Increased exposure of humans to noise is one problem of ongoing urbanization, leading to a range of adverse health impacts. Green spaces have come into focus as a potential means to mitigate such negative effects. As part of the project RESTORE (Restorative potential of green spaces in noise-polluted environments), this laboratory study investigates pathways of (a) stress buildup from noise exposure/cognitive load and (b) stress reduction in recreational areas. During a stress phase, participants were exposed to road traffic noise scenarios of different sound pressure levels (L_{Aeq} of 35 dB, 55 dB, 75 dB). Half of the participants listened to the sound situations for 10 minutes attentively, while the other half completed different cognitive tasks. Afterwards, in the restoration phase, participants were audio-visually immersed in a VR environment for 20 minutes. Half of the participants experienced a quiet natural green space, the other an urban non-green space with faint urban sounds of comparable level. Results show that perceived stress increased with cognitive load and—to a lesser extent—with L_{Aeq}. The beneficial effect of natural green was demonstrated by several measures of perceived restoration, all pointing towards a significantly higher psychological recovery in green spaces than built urban areas.

Keywords: Noise, Stress, Green, Cognitive Test

INTRODUCTION

Noise can act as a stressor upon humans[1,2]. Unfortunately, increasing urbanization and densification often entails exposure to noise from different sources such as from transportation. Various detrimental effects of noise have been documented. They pertain, among other things, to human physiology[3,4], psychology[5] and cognition[6,7]. To counteract potential long-term effects of (noise-related) stress, restoration is essential. Restoration research has identified the beneficial role of natural green[8,9] in replenishing attentional resources[10,11], stress-sensitive biomarkers[12] and as a general 'mood-brightener'[13,14]. Among the most influential theories to explain this phenomenon are the *Attention Restoration Theory*[15], which posits that engaging with nature does not deplete attentional resources as opposed to non-green environments, and the *Stress Reduction Theory*[16], which understands stress recovery as a quick physiologically measurable process initiated by positive affective responses to the environment and relaxation triggered by perception of vegetation or water. Interestingly, it is not only the *'touchable'* and *'smellable'* forest that provides restoration potential: Even virtual versions of natural greenness presented in laboratory studies, lacking any haptic and olfactory sensory information, contribute to stress recovery[17,18].

In this paper, we describe our investigation into psychological effects of stress and subsequent restoration in virtual reality (VR) environments. This is the first laboratory experiment within the RESTORE project (www.restore-project.ch)—an interdisciplinary and holistic investigation into stress buildup and the restorative potential of green spaces.

MATERIALS AND METHODS

Study Design

We studied two factors that are known to impact stress levels of humans: noise and cognitive load[4,19]. In terms of stress recovery, we studied the restorative factor of 'Greenness'. Noise, the first stress factor, comprised three levels pertaining to the A-weighted equivalent continuous sound pressure level L_{Aeq}: 35 dB, which corresponds to very light ambient sound; and road traffic noise of 55 dB or 75 dB (more details in the *Materials* section). Task, the second stressor, manipulated the cognitive load a participant was exposed to. It was comprised of two levels: one group had to perform a series of cognitively demanding tasks under time pressure (mental arithmetic/MPA[19,20], Stroop task[21]) and the control group listened to the noise stressors attentively without performing cognitive tasks. Henceforth, we classify the two task groups as 'high demand' and 'low demand', respectively. Finally, VR setting was the stress restoration factor that determined in which environment the participant recovered from stress: in a natural green space or an urban built (non-green) space. Both restorative spaces were equally quiet (L_{Aeq} 47.5 vs 47.1 dB, respectively). All three factors were manipulated between-participants, so that each person was randomly assigned to one factor combination (out of 18 pathways in total).

Participants

We recruited 96 participants (M_{age} = 39.4±14.6 [18–77]; 47 male, 49 female), based on power calculations, assuming a large effect size (16 subjects per pathway [3 exposure levels × 2 tasks] for stress phase; 48 subjects per VR pathway (green, built) for restoration phase). They received 50 Swiss Francs for their participation as compensation.

Apparatus

The experiment took place at the first author's institution in an acoustically treated room with 20 satellite loudspeakers distributed in a hemisphere around a center point (where the participant sat) plus four distributed subwoofers in the room's corners. The background noise in the lab lies below an L_{Aeq} of 7 dB.

Materials

Stressor Stimuli

Three 10-minutes long road traffic noise stimuli served as auditory stressors. The quietest stimulus, with an L_{Aeq} of 35 dB, was a recording taken from a quiet urban space in the city of Zurich, Switzerland (distant light traffic). Furthermore, two road traffic noise scenarios were auralized, i.e., rendered audible, using parametric sound synthesis tools[22]. One scenario, with a receiver location 6 m from a densely trafficked four-lane street (50 km/h, 1000 veh/h/lane) had an L_{Aeq} of 75 dB. The second scenario, with the same street at a distance of 30 m and an additional 2 m high noise barrier between street and receiver, had an L_{Aeq} of 55 dB. Additionally, the soundscape from the 35 dB recording was added to the 55 dB and 75 dB auralizations as background noise, which was effectively inaudible.

Restoration Stimuli

Audio-visual recordings were taken from a natural green space and from a built urban space in the city of Zurich (see Figure 1). The visual settings were recorded using a 360° monoscopic camera, and the spatial sound recordings were done with a Zylia 3rd order ambisonic microphone.

Figure 1. Screenshots of the two restorative spaces used during the VR session: a natural environment (panel A) and a built urban environment (panel B).

Audiovisual reproduction

The audio reproduction was implemented using 3rd order ambisonics and the visual information was played back using the head mounted display (HMD) Oculus Quest 2. All the development was done within the Unity game engine. For details on the development of the audio-visual setup, the reader is referred to the dedicated publication[23].

Questionnaires

The entire experiment was completed in German. In this article, we provide the English translations for the questions presented to the participants.

Perceived Stress, Wellbeing, Noise Annoyance. We asked the participants the three questions (in random order of appearance): '*How stressed do you feel at the moment?*', '*How well do you feel at the moment?*', and *'How much did the surrounding sound environment annoy or disturb you?*', once after they completed the stress phase and once after they completed the restoration phase, in order to assess the participant's (pre- and post-restoration) perceived stress level, wellbeing, and noise annoyance, respectively. To answer the question, the participants used a 11-point numerical scale (from 0 to 10, labeled additionally with the two verbal anchors '*Not at all*' and '*Extremely*', modeled after the ICBEN numerical scale[24]). In addition, one question asked the participants whether the VR immersion caused them *dizziness*, *unease* or *nausea* (yes/no).

Perceived Restoration. We assessed subjectively perceived restoration after the 20-min VR restoration phase with three different measures. Firstly, the abbreviated 11-item version of the *Perceived Restorativeness Scale (PRS-11, or PRS for simplicity)*[25,26] assesses the general attitude toward four restorative qualities of environments: Fascination, Being-away, Coherence and Scope. Secondly, the actual evaluation of the VR experience is reflected in the *Restoration Outcome Scale (ROS)*[27]. Here, the six questions assessed, whether the participants feel calmer, restored, energized, more focused than before and if they were able to forget their troubles (unburden) and order their thoughts. Finally, we assessed the restoration potential of the space with a one-item question (short *1Q*; *"I can recover from stress in this environment."*). All three instruments used a 7-point verbal scale (from '*not true at all*' – '*completely true*').

Procedure

The experimental procedure comprised two main phases: First, a stress phase during which participants were exposed to a particular stress condition. Second, a restoration phase, during which participants recovered. Participants were tested one by one. The experiment started with reading the study information and signing the informed consent form. Then, they were seated in the center spot of the laboratory.

Stress Phase

Half of the participants were asked to listen attentively to the 10 min audio playback (low demand group), while the other half of the participants were told to solve cognitively demanding tasks during the 10 min audio playback, which appeared on a touch screen before them (high demand group). The cognitive tasks consisted of 5 min MPA task and a 5 min Stroop task. After untimely responses, the feedback 'TOO SLOW!' ('ZU LANGSAM!' in German) appeared on screen for 1 sec; after incorrect responses, the feedback 'WRONG!' ('FALSCH!' in German) appeared. After the stressor task was completed, three questions followed in random order, asking people for their perceived stress, wellbeing, and noise annoyance.

Restoration Phase

After finishing the stress phase, the experimenter entered the room to help with the attachment of the HMD for the VR application. Half of the participants spent the restoration phase in a natural green space, half spent it in a non-green urban space (see *Materials* for details). After the 20 min had elapsed, the VR application terminated automatically and the experimenter entered the room to detach the HMD. The experiment concluded with the second part of the questionnaire (see *Materials* for details). In total, the study took approximately 53 minutes on average (*SD* = 4, range 46-68 min).

Data Analysis

All statistical analyses were performed using *R* (version 4.1.2), specifically the packages *neatStats and BayesFactor*[28–30].

For the stress phase measures, separate two-way ANOVAs with the between-subjects factors Task (high demand vs low demand) and L_{Aeq} (35 vs 55 vs 75 dB) were performed for the ratings for perceived stress, wellbeing, and noise annoyance from all 96 participants.

For the restoration phase, separate two-way ANOVAs with the same factors were performed, but this time on post-pre restoration differences for these three measures, to determine their progression over the restoration period. For the absolute post-restoration ratings, pairwise comparisons per restoration setting (Setting: nature vs urban) were performed. To compare the effect of perceived restoration between nature and urban spaces, pairwise comparisons were performed on the three measures PRS, ROS, and 1Q (see *Materials*). For all analyses pertaining to restorative effects, we excluded those participants who reported dizziness, unease or nausea during the VR immersion (11 exclusions), due to the possibility that this state affected the restorative effect. This left 85 participants (M_{age} = 40.0±14.3 [19–77]; 44 male, 41 female) for restoration-related analyses.

Welch's *t*-tests were performed for any pairwise comparisons, unless the Shapiro-Wilk test indicated non-normal distribution ($p < .05$), in which case the nonparametric Mann–Whitney *U* tests were performed. In addition to effect sizes (partial eta squared η_p^2 for ANOVA; Cohen's *d* for *t*-tests), Bayes factors (BF) are reported ('medium' *r*-scale of 0.5 for ANOVA and 0.707 for *t*-tests). A Bayes Factor compares the likelihood of two competing hypotheses (here, the null and alternative hypothesis) based on the observed data[31], whereas *r*-scales reflect a-priori expected effect sizes[32]. BF supporting the null hypothesis are denoted BF_{01}, those supporting the alternative hypothesis are denoted BF_{10}. Typically, a Bayes factor greater than 3 is considered as providing "substantial" evidence for one hypothesis over the other[33]. Note that in addition to the psychological measures we focus on here, we also assessed galvanic skin response and salivary cortisol in the course of the study. As we do not report results pertaining to these physiological measures in the context of this paper, we will refrain from referring to all procedural steps associated with them.

RESULTS

Stress Phase

Perceived Stress: The main effect for Task was significant, with $F(1, 90) = 31.50$, $p < .001$, $\eta_p^2 = .259$, $BF_{10} = 5.27 \times 10^4$. Figure 2A shows that the high demand group displayed higher perceived stress than the low demand group. A main effect of L_{Aeq} on perceived stress was not supported by the data, with $F(2, 90) = 2.41$, $p = .095$, $\eta_p^2 = .051$, $BF_{01} = 1.57$. The interaction between the factors was not significant ($p = .419$).

Wellbeing: The main effect for Task was significant, with $F(1, 90) = 17.80$, $p < .001$, $\eta_p^2 = .165$, $BF_{10} = 349.63$. Figure 2B shows that participants in the high demand group reported lower wellbeing than the low demand group. The main effect for L_{Aeq} was significant, but BF indicated no convincing evidence in favor of the effect, with $F(2, 90) = 3.74$, $p = .027$, $\eta_p^2 = .077$, $BF_{10} = 1.87$. Pairwise comparisons showed that the 35 dB group reported significantly higher wellbeing than the 55 dB and the 75 dB group ($U = 673.50$, $p = .026$, $d = 0.52$, $BF_{10} = 1.35$; $U = 707.00$, $p = .007$, $d = 0.59$, $BF_{10} = 2.33$, respectively), but again, BF indicate no substantial support for either of the hypothesis tests. The interaction was not significant ($p = .649$).

Noise Annoyance: Task did not affect noise annoyance ratings ($p = .965$). In contrast, the main effect of L_{Aeq} was significant, with $F(2, 90) = 20.33$, $p < .001$, $\eta_p^2 = .311$, $BF_{10} = 3.12 \times 10^5$. Figure 2C illustrates how noise annoyance (NA) increases with increasing L_{Aeq}. Pairwise comparisons showed significant differences between all three groups: $NA_{35dB} < NA_{55dB}$ ($U = 305.00$, $p = .005$, $d = -0.69$, $BF_{10} = 4.89$), $NA_{35dB} < NA_{75dB}$ ($U = 140.00$, $p < .001$, $d = -1.56$, $BF_{10} = 514.72$), and $NA_{55dB} < NA_{75dB}$ ($U = 271.00$, $p = .001$, $d = -0.90$, $BF_{10} = 15.87$). The interaction term was not significant ($p = .367$).

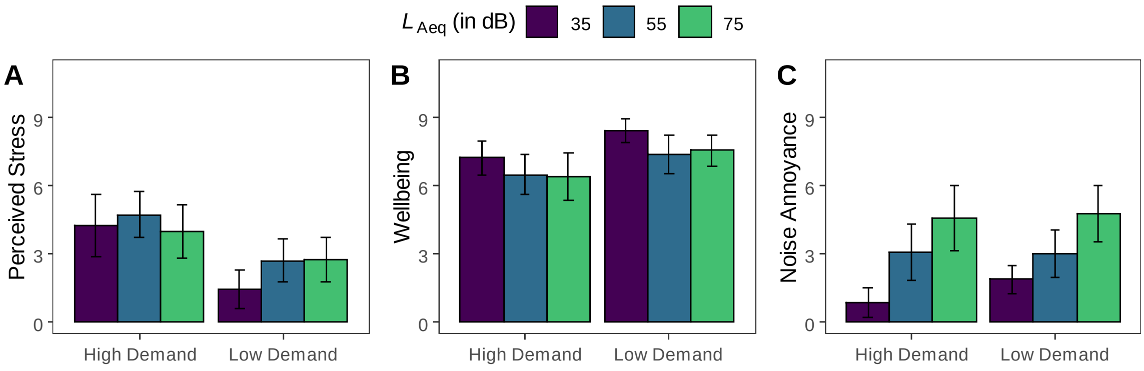

Figure 2. Mean ratings for perceived stress (A), wellbeing (B), and noise annoyance (C) per Task and L_{Aeq} group assessed after the stress phase. Error bars display 95 % CI of the means.

Restoration Phase

Perceived Stress, Wellbeing, Noise Annoyance. For the perceived stress progression score, the main effect for Task was significant, with $F(1, 79) = 14.23$, $p < .001$, $\eta_p^2 = .153$, $BF_{10} = 69.17$. The difference score was significantly lower in the high demand group than the low demand group, indicating stronger stress decrease in the former compared to the latter group. As displayed in Figure 3A, difference scores from the high demand group were nominally below 0, indicating less stress after the restoration than before. Conversely, difference scores from the low demand group were nominally above 0, indicating a slight stress increase after the restoration. As for noise exposure, the main effect for L_{Aeq} was significant, but BF indicated no substantial evidence for the effect over the null hypothesis, with $F(2, 79) = 3.24$, $p = .044$, $\eta_p^2 = .076$, $BF_{10} = 1.24$. Only one significant difference showed in follow-up pairwise comparisons: Participants with previous noise exposure of 55 dB indicated a larger (negative) difference score than the 35 dB group.

For wellbeing progression scores, no significant effects were seen. Figure 3B shows positive scores, indicating that wellbeing generally increased after the restoration phase for all groups.

For noise annoyance progression scores, the main effect for L_{Aeq} was significant, with $F(2, 79) = 6.64$, $p = .002$, $\eta_p^2 = .144$, $BF_{10} = 16.95$. Figure 3C shows that noise annoyance scores generally decrease with L_{Aeq}, with only two pairwise comparisons showing significantly different scores: $\Delta NA_{35dB} < \Delta NA_{55dB}$ ($U = 558.50$, $p = .014$, $d = 0.53$, $BF_{10} = 2.72$), and $\Delta NA_{35dB} < \Delta NA_{75dB}$ ($U = 586.50$, $p < .001$, $d = 1.04$, $BF_{10} = 19.60$), with only the BF of the latter comparison showing substantial evidence that post-pre noise annoyance was lower for the group previously exposed to the highest noise (75 dB) than for the group previously exposed to the lowest noise (35 dB). Finally, nonparametric pairwise comparisons revealed that the restoration setting (nature vs urban) did not significantly affect the final (absolute) post-relaxation ratings for the three measures (see Table 1).

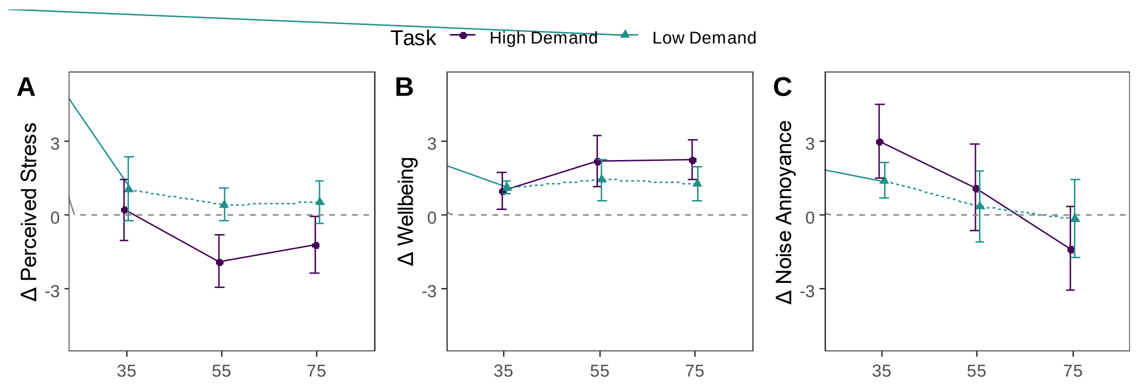

Figure 3. Difference scores of post minus pre-restoration ratings for perceived stress (A), wellbeing (B), and noise annoyance (C) per task and L_{Aeq} group. Error bars display 95 % CI of the means.

Table 1. Arithmetic means ± standard deviations of the restoration phase related ratings for perceived stress, wellbeing, and noise annoyance per VR setting.

Measure	Nature	Urban	Test Statistic: Nature vs Urban
Perceived Stress	3.3±2.0	3.0±2.0	U = 982.50, p = .473, d = 0.12, BF_{01} = 3.54
Wellbeing	9.0±1.4	8.7±1.3	U = 1008.50, p = .336, d = 0.20, BF_{01} = 2.91
Noise Annoyance	3.5±2.8	4.1±2.4	U = 695.00, p = .064, d = –0.25, BF_{01} = 1.56

Perceived Restoration. Since the PRS, ROS, and 1Q ratings all measure some aspect of perceived restoration, the Bonferroni corrected α-level for the three pairwise comparisons between the two restoration settings (nature vs urban) reported here is .017. The means for the individual factors of both, the PRS and the ROS, are displayed in Figure 4. The PRS score (mean of all 11 items) in the nature group was significantly higher than in the urban restoration group, with $t(80.6) = 7.26$, $p < .001$, $d = 1.56$, $BF_{10} = 3.11 \times 10^7$. The analysis of the overall ROS score confirmed the result and showed significantly higher perceived restoration in the nature compared to the urban space, with $t(80.9) = 2.66$, $p = .009$, $d = 0.58$, $BF_{10} = 4.73$. Finally, the one-item question (1Q) corroborated the significantly higher restorative potential of natural compared to urban built spaces, with $U = 1370.50$, $p < .001$, $d = 0.96$, $BF_{10} = 62.72$.

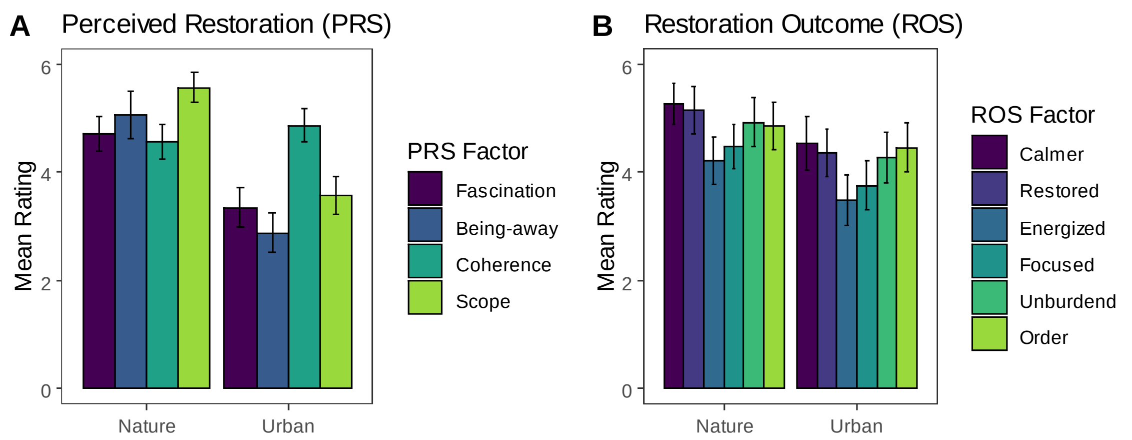

Figure 4. Mean ratings of Perceived Restorativeness (A) and Restoration Outcome (B) per restoration group (nature vs urban) after the VR immersion. Error bars display 95 % CI of the means.

DISCUSSION

In this laboratory study we investigated the effect chain from stress induction to stress recovery using a VR methodology.

Stress

First, we investigated stress buildup brought about by two different triggers: cognitive load and noise exposure. Since both are known to cause stress to humans, we assessed the psychological evaluation of these stressors in isolation and in tandem. We compared one group of participants who performed cognitively demanding tasks during noise exposure to a control group who focused on listening to the sounds. Cognitive load reliably induced stress and reduced wellbeing. The effect of noise on perceived stress and wellbeing was generally small. Nevertheless, increasing L_{Aeq} tended to negatively impact participants, being linked to somewhat higher stress and lower wellbeing ratings. Noise annoyance, on the other hand, was clearly associated with the L_{Aeq} (the higher the L_{Aeq} of the stressors, the higher the annoyance), demonstrating that our manipulation was successful and the auralized sounds were perceived as intended. Task had no effect on noise annoyance ratings, suggesting that accomplishing a task neither raised nor lowered the perceived nuisance of noise.

Restoration

As the analyses of the progression scores showed, people in the high-stress conditions (high demand group; 55-75 dB noise exposure) reported a decrease in perceived stress after the restoration phase. Further, all participants' wellbeing increased, irrespective of the previous stress condition, indicating that the stress phase negatively affected participants, even in the "lowest" stress conditions. The change in noise annoyance showed that the group previously exposed to 75 dB reported a reduction after the restoration phase compared to the 35 dB group. With L_{Aeq} slightly above 47 dB, the VR audio was louder than the L_{Aeq} of 35 dB, which explains the positive scores (i.e., increased noise annoyance) in this group. Overall, these psychological effects were according to expectations and are good indicators for the success of the experimental manipulations.

As for the investigation of the effect of nature on restoration, the comparisons of perceived stress, wellbeing, and noise annoyance post-restoration between the nature and urban group did not yield any differences. However, all three measures of perceived restoration indicated that nature was evaluated as more restorative than the built urban space. Using the *Perceived Restorativeness Scale*[25,26], we showed that green spaces are generally evaluated as showing higher potential for (attention-related[15]) restoration. With the *Restoration Outcome Scale*[27], we directly assessed the restorative effect of the VR phase in our lab setup. Its overall score showed that nature contributed to a greater extent to perceived restoration than did the urban space. The greenness advantage was again corroborated by the third instrument, the 1-question item, a judgment made about the overall potential to recover from stress. Evidence for the nature advantage in perceived restoration was substantial and effect sizes ranged from medium to large.

Limitations

In order to maximize control during the restoration phase, our participants restored in a VR environment in a lab. With this come the 'common' limitations of reduced realism and ecological validity that apply to laboratory studies in general. However, firstly, the long history of restoration research has cross-validated findings from virtual and real-life stimuli[11,34]. In a similar fashion, this laboratory experiment is part of the RESTORE project, which will strategically compensate limitations of one methodology with the strengths of another (e.g., ecological validity, degree of control). For instance, a field experiment within RESTORE takes the design of the current lab study into real life: It tests stress-recovery under real-life conditions by performing guided-walks with the participants in forests and built urban areas, similar to our VR spaces.

Outlook

As mentioned above, we also collected physiological measures during the experiment to investigate changes in electrodermal activity and salivary cortisol in response to noise exposure, cognitive demand, and restoration setting. The analyses of these measures will be reported in a later publication.

With the solid evidence for increased psychological effects of restoration in natural sceneries unearthed in this experiment, the question remains, which factor or factors are primarily responsible: the visual "greenness" or the natural soundscape? This question will be addressed in a follow-up study, which will investigate the audio-visual requirements for restorative spaces by systematically combining different visuals (forest, lake, urban) with different soundscapes (natural vs anthropogenic). The goal is to disentangle the two potentially contributing factors Landscape and Soundscape, which up until now are still very much intertwined[35]. Stimuli in the follow-up study will be presented using VR again, since the present experiment demonstrated that our VR methodology was successful in eliciting restoration effects.

CONCLUSION

Restoration from stress is a crucial need of modern human society. Virtual reality is a relatively novel way to study this relief from stress in the laboratory, be it noise-related or induced by cognitive load. In this laboratory study, we investigated psychological stress buildup due to cognitive load and noise, and stress restoration in two restorative areas (natural and built environment). We found that the buildup of perceived stress depends mostly on highly demanding cognitive tasks but much less on noise exposure, while the opposite was true for noise annoyance. Stress reduction depended on the stress phase (stronger restoration after cognitive task than after pure exposure to noise), while annoyance reduction was stronger in groups previously exposed to higher road traffic noise. While stress levels after restoration were similar between natural and built environments, natural green environments have a considerable advantage in the feeling of restoration compared to (equally quiet) built urban spaces.

Acknowledgements

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