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The effect of vertical façade greenery in virtual urban environments on human emotion

Delia Lendenmann[1*], Sara Irina Fabrikant[2]

[1] Independent Scholar, Aarau, Switzerland
[2] Department of Geography and Digital Society Initiative, University of Zurich, Zurich, Switzerland

Correspondence: Sara Irina Fabrikant (sara.fabrikant@geo.uzh.ch)

Abstract. Already more than half of the global population is living in urban areas today. Rapid urbanisation during the past decades has brought about a significant loss of green space in the built environment across the globe. To mitigate the loss of horizontal green space, vertical façade greenery has been promoted as one promising way especially in increasingly densifying and expanding urban areas. Façade greening has also been promoted to strengthen (mental) health and wellbeing of the ever-increasing urban population in the expanding built environments. To investigate the contribution of façade greening to the wellbeing of urban citizens, we set out to empirically study the influence of green building façades, experienced in virtual reality, on human emotion using self-reports and psycho-physiological measurements. As hypothesized by prior work, we indeed find that participants feel less aroused and thus more relaxed in virtual urban environments experienced with green building façades compared to regular building façades without any greenery. With these promising empirically validated results we shed new light on mental health benefits of vertical greenery in urban environments.

Submission Type. Theory, experiment

BoK Concepts. Graphic representation techniques, Web visualization in 2D and 3D, Use of geospatial information in environmental issues

Keywords. Urban, UNSDG 11, vertical green space, emotion, experiment, virtual reality

1 Introduction

By 2050, two-thirds of the global human population will be living in urban areas (UNSDG, 2024). Increased urban sprawl and the densification of cities due to pressing housing needs are associated with an increasing loss of horizontal green space in the built environment (Bille et al., 2023). This is problematic for many reasons and operates at multiple spatial scales, because green spaces contribute positively to the urban climate, its biodiversity, and the well-being of city dwellers, human and animals (Baumann & Brooks-Cederqvist 2023). As a result of climate change, green spaces in cities help to reduce threats to the health of city dwellers. Health issues of citizens have intensified due to increasing air pollution because of rising traffic congestions in the built environment, increasing air temperatures because of heat island effects in inner cities, and alongside of the loss of greenspaces and their biodiversity. Green spaces in cities also play an important role for mental health of their citizens (WHO), as walking and cycling surrounded by greenery have shown to contribute positively to everyday tress management of city dwellers and thus greenery have generally shown to have a beneficial effect on human health (Tyrväinen et al., 2014). For example, the direct exposure to and apprehension of plants, leads to positive psychological states in humans, and in a related increase of physiological brain activity (Jang et al., 2014). More recently, vertical greening systems, also more commonly known as façade greening (Radić et al., 2019) have been promoted in cities to mitigate the loss of horizontal green space, and to attenuate possible negative effects of densification in cities (Sheweka and Mohamed, 2012).

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The *vertical forest* high rise building in Milan (IT) is an early, internationally renowned architectural example for vertical green space (Figure 1).

Figure 1. Vertical forest high rise (Stefano Boeri Architetti 2014)

However, to date, little is actually known about how façade greenery might impact human relaxation and the (mental) well-being of citizens (Elsadek et al., 2019; Radić et al., 2019). Of the few existing empirical studies that have looked at the effect of (horizontal) greening in cities, most, are based on respondents' self-reports and beliefs (Baumann and Brooks-Cederqvist, 2023), and have been carried out with static, 2D experimental (image) stimuli. Suggestions for future work in this related, prior literature have already been made to carry out future empirical studies in the real world or at least, in immersive virtual reality to increase ecological validity (Weinberger et al., 2021, 2022) of empirical studies. One urban VR study looked specifically at stress buffering effects of vertical greenery, while participants were being exposed to noise pollution along busy streets, but with inconclusive results (Chan et al. 2021). With the present study, we aim to contribute to these still existing research gaps.

2 The present study

We set out to empirically investigate how the presence of vertical greening, that is, green building façades, presented to participants in an immersive (head-mounted) virtual urban environment would directly influence their current emotions. To capture participants' emotions, we wished specifically to couple subjective self-reports with objective psychophysiological measurements. On the one hand, we used a standardized emotion self-report instrument, the self-assessment-manikin (SAM), to record the strength (i.e., arousal) and the quality (i.e., valence) of study participants' felt emotions (Bradley and Lang, 1994). We also congruently measured participants' psychophysiological arousal, using the electrodermal activity (EDA) sensing method (Boucsein, 2012). We hypothesize that the perception of green façades in a virtual urban environment would yield a relaxing effect in participants during and after exposure time (i.e., experimental group), as measured by a reduction in participants' excitement (i.e., arousal) and tension (i.e., negative valence), compared to participants who are exposed only to building façades without any vertical greenery (i.e., control group).

2.1 Methods

We developed a controlled lab experiment using a head mounted virtual reality (HMD VR) set up to test our hypotheses on the potential effects of green building façades on participants' reported and psycho-physiologically measured emotions (i.e., arousal and valence). We specifically adopted a mixed 2 (between factor façade type, two levels: with/without vertical greening) x 5 (within factor scenery, five levels: five urban scenes) subject design. We assigned participants randomly to the two experimental groups. One group was only exposed to urban scenes containing buildings with green façades (Figure 2B), while the control group was only shown the same building façades and urban scenes

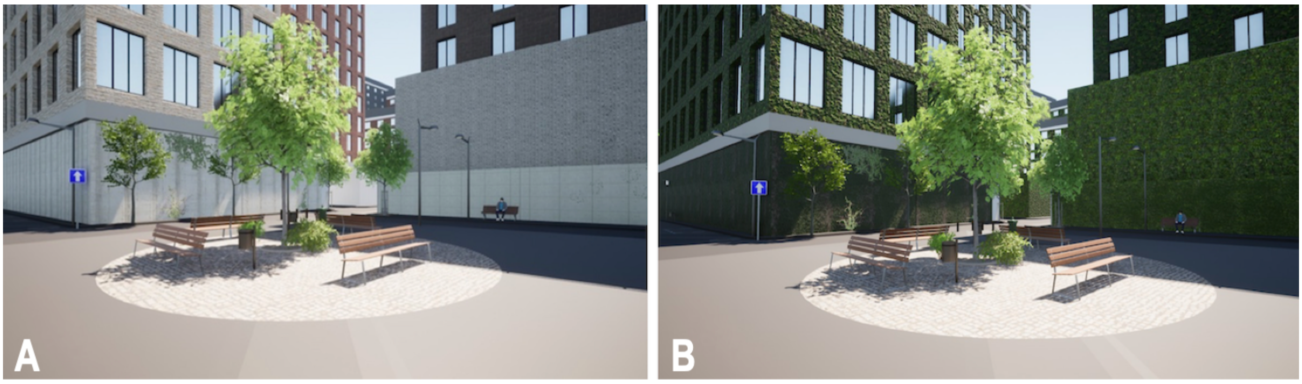

Figure 2. Virtual urban scene stimulus without green façades (A), and with green façades (B).

without any vertical greenery (Figure 2A). All participants experienced the same five urban scenes, but at different positions in the viewing sequence. This, because we were specifically interested to assess the evolution of their (relative) arousal and valence over exposure time. We hypothesize that the continued exposure to green façades in the experimental group would have a restorative effect on participants, including a positive (i.e., calming) effect on the recorded valence, and also a relaxing effect, thus leading to a reduction in participants' arousal measurements over exposure time.

2.1.1 Participants

Based on a power analysis run with G*Power (Faul et al., 2007) we aimed for a minimum of 16 participants per experimental group. Inspired by prior related research (Elsadek et al., 2019), we specifically aimed to invite people who are exposed daily to urban situations in their everyday lives. Because our study is specifically motivated to contribute to the earlier mentioned UNSDG Goal 11 *"Make cities and human settlements inclusive, safe, resilient and sustainable"* (UNSDG, 2024), participants who live, work or study in a city served as a study inclusion criterion. We also applied three exclusion criteria to our participant sample. Firstly, because of their influence on psycho-physiological measures such as pulse or blood pressure etc. (Giuseppe et al., 2012) including perception and reaction speed (Rapoport and Baniña, 2007), we excluded participants who reported the use psychotropic drugs. Secondly, we excluded participants suffering from achromasia, a color vision deficiency, as the perception of green colored objects is central to our study. Thirdly, because we aimed to measure changes in emotion over exposure time, we first showed all participants the same exciting video of a roller-coaster ride at the beginning of the experiment. This was done to induce high positive arousal to all participants at the beginning of the experiment to serve as a baseline, with the aim to measure *arousal and valence changes* over exposure time. Because of this, we also excluded participants who reported to suffer from severe anxiety of roller-coaster rides. We eventually were able to recruit thirty-six participants to take part in this experiment, run at the University of Zurich in the GIVA CAVE lab of the Geography Department. Due to unforeseen technical issues, we could only analyze the collected data of thirty-four participants, with an age range of 21–71 years (females=22, mean=31.2, STD=13.6 yrs.; males=12, mean=32.3, STD=15.7 yrs.). Of those, eighteen participants (52%) reported to have already been exposed to VR before taking part in our study. None violated any of the exclusion criteria.

2.1.2 Materials

We developed the virtual urban scenes from scratch, using a freely available, low-resolution and untextured model of a densely built city, comprising many high-rise buildings with a mix of broad avenues and narrow streets. We downloaded the model in FBX format from the *Turbosquid* website to be imported to *Twinmotion,* a 3D modeling software specifically targeted to urban planners and landscaping professionals. We chose this particular tool because it is based on the state-of-the-art *Unreal Engine* technology, known to provide high-quality and aesthetically attractive photorealistic renderings. We then selected five suitable locations in the chosen city model that included a variety of typically encountered urban scenes in a densely built city (Figure 2). As climbing plants such as ivy or Ficus pumila (Sheweka and Mohamed, 2012) are often used for green façades in the real world and which were already showcased in previous

Figure 3. A study participant is wearing the VR headset and the EDA wristband on their left hand during the experiment (A). The SAM questionnaire is displayed in the virtual environment front of an urban scene stimulus with green façades (B).

related work (Elsadek et al., 2019), we also selected this Ficus plant for our green façade stimuli (Figure 2B). We then implemented one urban scene sequence for each experimental group in Twinmotion (two in total), each containing ten scenes, to be displayed in random order to each participant wearing a HTC-VIVE Pro2 headset, running the SteamVR Tracking 2.0 software. Stimuli were rendered at a spatial resolution of 1440 x 1600 pixels per eye, with a 90 Hz refresh rate, and a field of view of 110 degrees. An adjustable headband allowed the VR headset to be individually fitted for each participant (Figure 3A). This setup was selected because it allowed participants to actively look around in the 3D scene.

We first ran a pilot study with only a handful of participants not re-invited to the main experiment to test our equipment, the developed urban scene stimuli, and the planned procedure. This pilot suggested to reduce the initially implemented ten urban scenes per group to a maximum of five scene stimuli per sequence. We thus reduced the sequence to five stimuli, to reduce the potential for simulator sickness and respective unwanted EDA confounds. For the same reason, we also chose a seated position for participants during scene viewing, as further explained in the procedure section below.

2.1.3 Procedure

After arriving at the VR testing lab, participants were given written information on the goals of the experiment and about the experiment procedure. They were then invited to sign a consent form. Following that, participants were comfortably seated on a swivel chair that could not otherwise be moved, and they were then helped to don the VR headset (Figure 3A) and to put the Empatica E4 wrist sensor on their non-dominant hand to capture their psychophysiological arousal state (EDA) and pulse during the experiment (Figure 3A).

To look around the displayed scene, participants were able to freely rotate their bodies (360 degrees) and to move their head, while being seated on the office chair. As mentioned earlier, all participants were shown an identical two-minute roller coaster video at the beginning of the experiment, with the aim to generate an elevated arousal state that would serve as a baseline for subsequent relative arousal and valence ratings, and respective EDA recordings. We then assigned participants to one of the two experimental groups (with/without green façades) using a random number generator. Participants were asked to rate their felt emotion (i.e., arousal and valence ratings) using the SAM instrument mentioned earlier, displayed directly in the HMD VR display after each scene stimulus (Figure 3B). Participants were shown five urban scenes for 30 seconds each, in randomized order, followed directly by the SAM questionnaire after each experienced scene. After that, we administered an online questionnaire using LimeSurvey (LimeSurvey GmbH, n.d.) to get additional participant feedback. For this part of the study, participants did not wear the HMD VR gear. The first part of the questionnaire consisted of open-ended questions about participants' general perceptions and felt emotions during the scene viewing portion of this study. The second part of the survey contained a series of closed-ended questions about participants' viewing experience such as, their felt aesthetics of the seen façades, their urban façade preferences, etc. while also being presented with a randomized sequence of the full set of ten urban scenes, that is, with and without green façades, presented to them as static, 2D images. After that, participants responded to a few demographic questions, and were eventually asked to rate their current emotional state again. Finally, they were thanked and given a small token

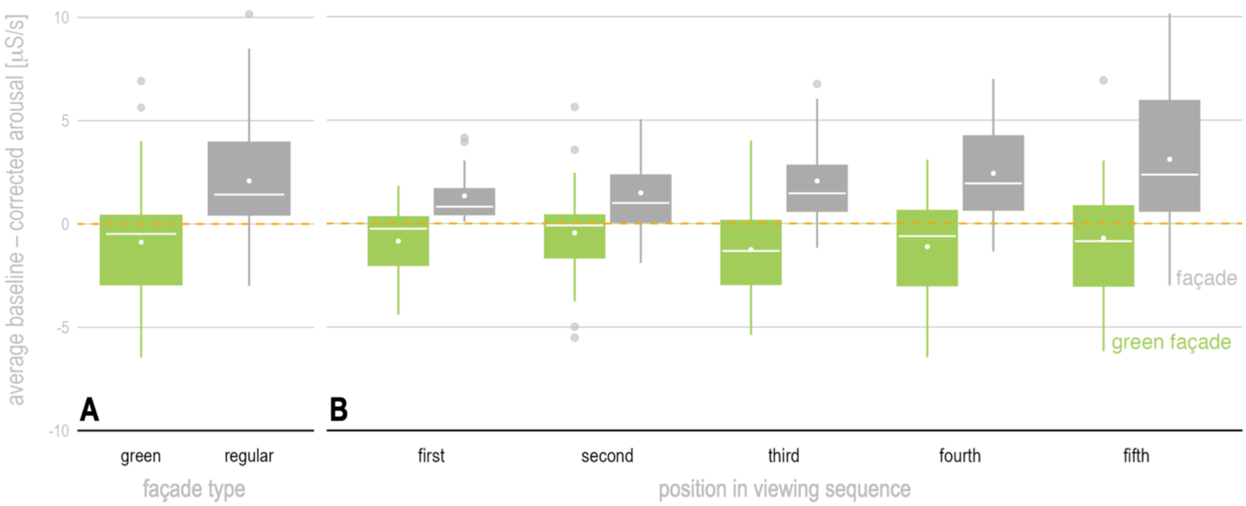

Figure 4. Participants exposed to green building façades show lower psychophysiological arousal (**EDA**) overall, compared to participants who experienced regular façades (A). The arousal differences between façade types increases over exposure time (B). [dots = mean, bars = median, +/- 1.5 IQR].

of appreciation for participation. The entire procedure lasted approx. 30 minutes in total.

3 Results and Discussion

Due to space limitations, we present only a subset of our findings herein, focusing on participants' arousal states, collected with the EDA measurements (Figure 4) and their felt emotions registered with the SAM self-reports (Figure 5), respectively. All response data were baseline-corrected for each participant for the statistical group comparisons, and thus represent average *changes* in arousal over the duration of the experiment, and in comparison to induced average arousal with the roller coaster video shown at the beginning of the experiment. Because we randomized the urban scenes in the viewing sequences, we report results on the viewing position, that is, from the first to fifth presented urban scene, irrespective of the particular urban scene that participants experienced. A respective comparative analysis on the actual scene stimuli did not reveal any statistical differences between scene characteristics. We adopted an α = .05 significance level for all statistical tests and interpret effect sizes according to Cohen (2013). Because some of the response data did not follow the normal distribution, we ran a mix of non-parametric tests (i.e., ART ANOVA, Mann Whitney, etc.) in R (4.3.1), and a repeated measures GLM in SPSS (29.0.2.0).

The results depicted in Figures 4 and 5, respectively, follow an identical structure. The plots in the A-panels of the Figures show overall central tendencies (means and medians) and the spread of the emotion response data overall across experimental groups, and in comparison to the roller coaster baselines (SAM: black solid line at zero, EDA: orange dashed line at zero). The result graphs in the B-panels of the Figures display on the x-axes the sequence of individual scene stimuli over the duration of the experiment, and respective statistical outcomes for the for the EDA measurements (Figure 4B) and SAM arousal ratings (Figure 5B), again after baseline correction.

In Figure 4, EDA *difference* values that are above (the orange dashed) roller coaster baseline video (y-axis at zero) show greater arousal compared to the baseline, those below this baseline show less arousal, thus greater relaxation, compared to the baseline, respectively. Overall, on average, participants in the control group who only saw grey façades (grey box plots: M = 2.08, SD = 2.50) exhibit greater arousal than participants in the green façade group (green box plots: M = -0.88, SD = 2.61) in Figure 4A. Applying a repeated measures GLM, we find a significant difference across experimental groups, as hypothesized, with a medium sized effect size ($F(1,32) = 17.92$, $p < .001$, $\eta^2 = .36$). This pattern is consistent across individual viewing position (Figure 4B), and the differences between groups increase towards the end of the viewing sequence.

Given that a SAM rating of 1 indicates *greater arousal and thus tension,* and that of 5 indicates *less arousal thus greater relaxation,* respectively, greater positive SAM *difference* ratings above the roller coaster baseline video (solid black y-axis line at zero) indicate greater relaxation, or lesser felt arousal compared to the baseline video rating in Figure 5 (A+B).

There is a smaller arousal difference between the SAM ratings and the video baseline at the beginning of the experiment (first to third urban scenes in Figure 5B)

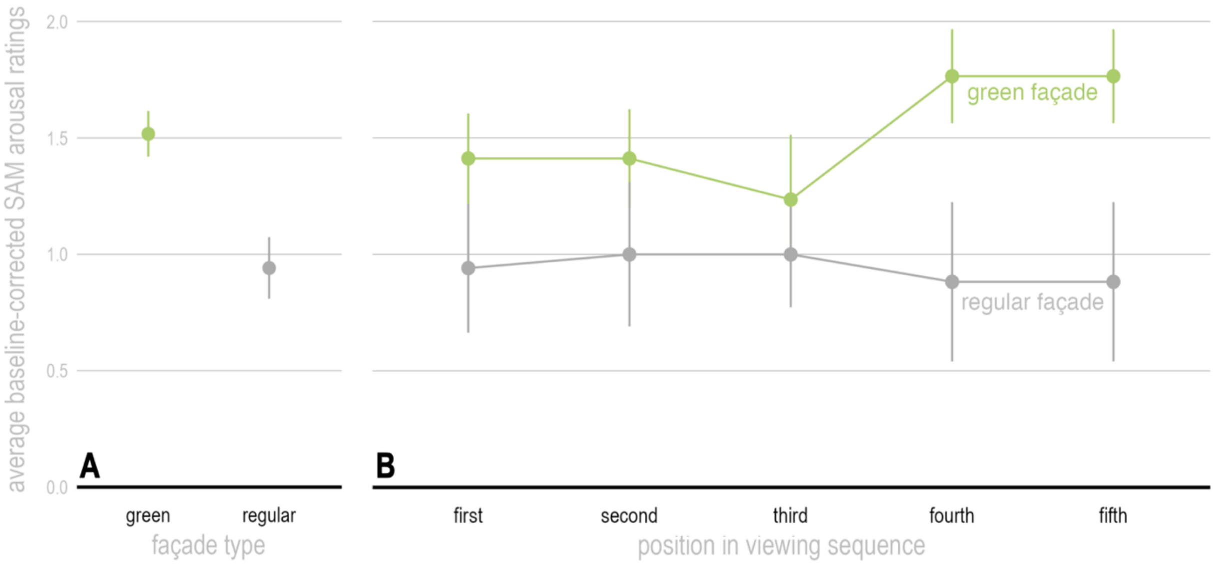

Figure 5. Participants exposed to the green façades report greater **SAM** relaxation ratings overall compared to participants exposed to regular façades (A). The relaxation differences between façade types increases over exposure time (B). [dots = mean, +/- SE]

which increases towards the end of the experiment (fourth and fifth urban scene). The SAM arousal ratings of the green façade group (green connected dots) exhibit consistently greater relaxation compared to that of the control group in grey (Figure 5B). After the third urban scene, this difference increases even sharply.

On average, overall, participants exposed to green façades rated the urban scenes as more relaxing ($M = 1.518$, $SD = 0.907$) compared to the baseline, and compared to the ratings of participants in the control group ($M = 0.941$, $SD = 1.218$) in Figure 5A. As hypothesized, we find this SAM rating difference between the two experimental groups to be significant overall ($W= 4666$, $p < .0006$). This difference represents a large effect ($r = .59$). The ART Anova (Elkin et al., 2021) run with façades and position factors (Figure 5B) also yields a significant and strong main effect for the façades ($F (1, 32) = 4.367$, $p < .05$, $\eta^2 = .81$).

Confirming and extending prior related work by Elsadek et al., (2019) and Tyrväinen et al., (2014), participants' arousal (SAM) ratings and measured EDA responses support our hypothesis that green building façades shown to participants in virtual urban environments lead to a reduction in their (negative) arousal. Participants who were only exposed to green façades in our HMD VR study felt increasingly more relaxed overall, compared to the control group who were shown building façades without any vertical greenery. This was expressed consistently in their self-reports and could be congruently observed it in their measured psychophysiological EDA responses.

Replicating arousal decrease and thus stress reduction which were previously found for exposures to green spaces in real-world conditions, we observed that participants became more relaxed over time when experiencing vertical greenery, that is, green façades also in virtual urban scenes as previous work had proposed, but not tested empirically (Weinberger et al., 2021, 2022). Conversely, we found an increase in self-reported and measured arousal (and tension) for the control group who were shown identical urban scenes but only without any vertical greenery. Aside from mitigating the loss of horizontal green space in increasingly dense and expanding urban environments, our promising results also shed new light on mental health benefits of façade greening in (virtual) urban environments, as already proposed elsewhere (Elsadek et al., 2019; Tyrväinen et al., 2014).

4 Conclusions and Future Work

We set out to empirically study the effect of vertical greening on human emotion in a head-mounted VR experiment. As hypothesized by prior work, we find that participants feel less aroused and thus more relaxed in virtual urban environments experienced with green building façades compared to regular building façades without any greenery. Vertical greenery, added to existing city infrastructure, may not only support the mitigation of horizontal green space loss, and the respective reduction in biodiversity due to urban sprawl and housing densification (Bille et al., 2023), but also offer new avenues on how to scaffold human stress reduction in the built urban environment (Tyrväinen et al., 2014; Ulrich et al., 1991).

All empirical findings come with limitations, however, and thus offer valuable opportunities for future work. While Jang et al., (2014) could show that human brain activity increases when people look at green foliage plants, compared to other plants, and this association may result in a more positive mental state for observers, our current study does not yet provide any further insights on whether relaxation happens because of the presence of plants or the apparent green color of their foliage. A future study could also investigate the type or quantity of façade greening in combination of existing horizontal green space. Because we only tested our hypothesis in HMD VR, to further increase ecological validity, of course, one could try to replicate a similar experiment in the real world.

Data and Software Availability.

Stimuli, scripts, and analyzed data are available at URL: https://gitlab.uzh.ch/giva/public/masters/delia.lendenmann.

Declaration of Generative AI.

Authors have not used any AI tools for the preparation of this manuscript. Authors attest that all the presented research is original, and has been conducted by authors themselves, without any AI assistance.

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