A Deeper Understanding of the Impact on the Restorative Quality of Green Environments as Related to the Location and Duration of Visual Interaction

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Abstract: This exploratory research aims to examine if the existence of vegetation in indoor environments affects people's attention levels. Also, do those elements receive more visual attention, or do they cause other elements in the space to stand out more visually? During experimental research, 182 residents of a high-rise residential building were randomly assigned to experience one of two versions of their building's lobby as a 3D virtual reality (VR) environment, one with and one without vegetation. Participants completed the Sustained Attention to Response Task (SART) twice, once before experiencing the lobby to establish a baseline of attention and once after, to assess possible improvement. Also, the amount of visual attention that each element received in the environment was calculated through gaze tracking. Results indicated that participants who experienced the lobby with vegetation showed meaningful improvement in their SART score. The gaze tracking heatmaps revealed that vegetation received significantly higher attention than all other elements. The analysis of the data demonstrated that those who gained the highest scores paid the highest amount of visual attention to vegetation. These findings suggest a positive relationship between the location and duration of visual attention and attention restoration level and that vegetation capturing non-voluntary attention may be among the major factors that positively impact attention restoration.

Keywords: Immersive Virtual Reality environment (IVRE), gaze tracking, attention restoration, sustained attention, vegetation

1 Introduction

This research aims to explore the role of vegetation in alleviating mental fatigue through tracking participants' gaze in an immersive virtual environment. Access to natural environments provides people with numerous health benefits (BAYCAN & NIJKAMP 2009, KENIGER et al. 2013). Urban residents' interaction with nature has decreased significantly due to population growth leading to densification. High-density development leaves fewer green spaces on the property (BARATI et al. 2013, HAMEDANI GOLSHAN & SAEDI 2017a, WANG et al. 2019) that leads to less urban green space, especially in larger cities (SAEDI 2014, HAMEDANI GOLSHAN & SAEDI 2017b, NOR et al. 2017). So, maximizing the benefit that city dwellers could receive by interacting with vegetation during the limited time and space that they have in their daily life seems crucial.

Different studies have utilized different modes of interaction with nature to measure various benefits of this interaction. The most common modes of virtual interaction with nature that have been utilized in measuring attention restoration and recovering from mental fatigue are 2D flat images (VAN DEN BERG et al. 2014), videos of nature (WANG et al. 2016, JENKIN et al. 2018), and 360 photographs (CHUNG et al. 2018, MORENO et al. 2018). Two dimensional

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images have the least alignment with a human's real-life experience in nature due to lack of motion or movement. Watching a video of nature from the human's point of view is more realistic since motion is involved. A limitation of videos is that individuals have no control over the pace or line of movement. 360° images, if experienced through VR goggles, are closer to a real human experience. In this experience, participants can move their heads around and look where they want and for the duration they intend. However, in this form of interaction, they still do not have the opportunity to move freely.

This study is using the immersive virtual reality environment (IVRE) since it can solve many of the limitations associated with the current virtual modes of interaction with nature (RICE & SAEDI 2021). Also, recent studies have demonstrated that experiencing IVRE could induce physiological and psychological responses in individuals similar to real world experiences (KULIGA et al. 2015, BAILENSON 2018, YIN et al. 2019, JIANG et al. 2021).

2 Research Methodology

The first research question of this study is, "Does the vegetation utilized in a multifamily residential complex's lobby design positively impact resident recovery from mental fatigue?". The second question is, if the positive impact exists, "which elements of the experienced environment receive more attention?" A quasi-experimental strategy was used to answer the research questions. In this research, attention restoration was the dependent variable, and the green element was the independent variable. Thus, the research explored if adding green elements to a building lobby can restore residents' attention (causal relationship). Given the number of variables involved, the researcher cannot establish a cause-and-effect relationship only based on the existence or non-existence of the green elements because several other non-measured factors could impact the relationship. However, data on where individuals look, and the duration of gaze will add valuable information regarding the nature of the elements that affect experience the most.

2.1 Sample Size

The sample for this study was 182 residents of the high-rise apartment. The participants were 37% female. All participants agreed to participate in the experiment voluntarily. The participants were between the ages of eighteen and sixty-five with no physical disabilities or visual impairments.

2.2 Study Site

As illustrated in Figure 1, the research study sites are two IVRE versions of an existing high-rise residential lobby. The vegetation was added to only one version. IVREs were modeled in Autodesk Revit 2020. The greenery was added to one model using Lumion. The Unity game engine was then utilized to allow participants to explore one of the two IVREs.

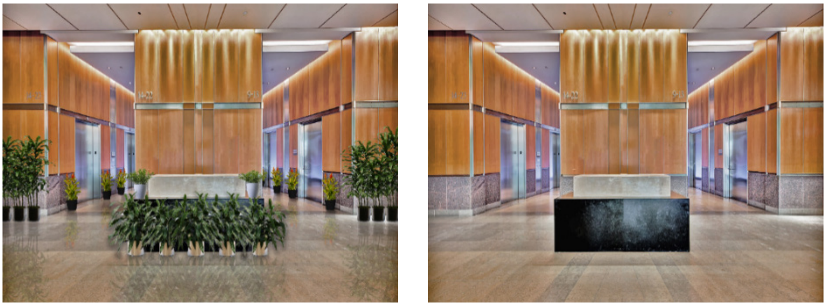

Fig. 1: Snapshots of the two versions of the lobby. The views are towards the building elevators

2.3 Data Collection Methods

2.3.1 Sustained Attention to Response Task (SART)

SART measures improvement in participants' sustained attention level as an indicator of attention restoration and cognitive performance (PERKINS et al. 2011). Sustaining attention is comprised of two discrete processes that occur in two separate parts of the brain. The dorsal attention network, located in the cortical part of the brain, helps individuals to perform a cognitive task (STURM & WILLMES 2001). These tasks require an individuals' voluntary attention. Surrounding distractors are filtered by the ventral attention network in the sub-cortical part of the brain (WARM et al. 2008, CORBETTA & SHULMAN 2002). This filtering process demands the intervention of an individual's in-voluntary attention. These processes are in effect simultaneously while performing a cognitive task. The SART test activates both dorsal and ventral brain networks (MANLY et al. 2003, SAEDI & RICE 2022).

During the SART test, two types of response variability can be measured. First, is the slow frequency variability (SFV). SFV reflects the progressive changes in response time variability during the task performance. Second, is the fast frequency variability (FFV) that reflects quick changes in response time over the course of the test (JOHNSON et al. 2007, JOHNSON et al. 2008). Changes in SFV demonstrate the arousal in the sub-cortical part of the brain and how it performs. Shifts in FFV reflects the changes in cortical attention control (JOHNSON et al. 2007, JOHNSON et al. 2008, SAEDI & RICE 2022).

2.3.2 Gaze Tracking

Gaze tracking locates the point of a person's gaze (fixation location) electronically. It can also follow and record the movement of the point of gaze (fixation duration) (F. VICENTE et al. 2015). The gaze-tracking system takes the center of the image that is rendered in front of the participants' eyes as the center of gaze. In this way, the software can record the gaze trajectory throughout the VR experience.

Data obtained from the gaze tracking was used to generate heat-maps that depicted the location and duration of visual attention, for each element in the two IVREs (DUCHOWSKI 2003, RAYNER 2009. LI et al. 2020). The HTC Vive Pro Eye virtual reality goggles were used for gaze tracking. Data obtained from the VR experience was then exported to iMotions 8.1 to generate heatmaps.

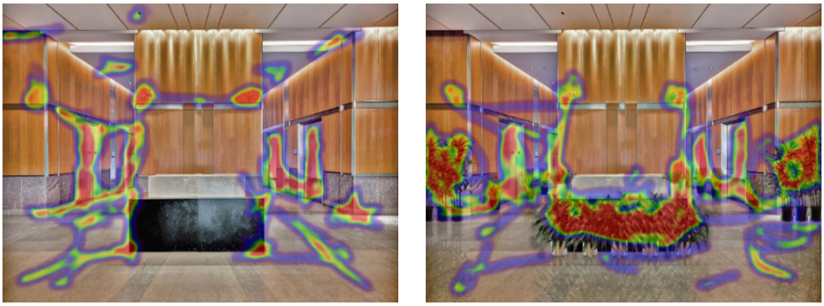

Fig. 2: Snapshots of the two cumulative heatmaps. Lobby with no vegetation (left); Lobby with vegetation (right)

A gaze-tracking point cloud was created for each participant. A cumulative point cloud was then created for each IVRE. Each point cloud was then normalized by the total fixation location and fixation duration of the two groups combined. The output of this process was used to generate one cumulative heatmap for each IVRE. The outputs were rendered in colors ranging from violet to red in a rainbow spectrum with violet representing the shortest fixation duration and red representing the longest fixation duration (Figure 1).

2.4 Procedure

The study took place at the end of the workday to increase the chance that participants were experiencing some degree of mental fatigue prior to starting the experiment. Participants, upon arrival at the residential complex, were moved to a separate space to complete a SART trial round and become comfortable with using the VR gear. After these orientation tasks participants completed the pre-immersion SART tests. The orientation and the SART test were conducted in a climate-controlled room with minimum external distractions. Conditions in the room were kept the same for all participants.

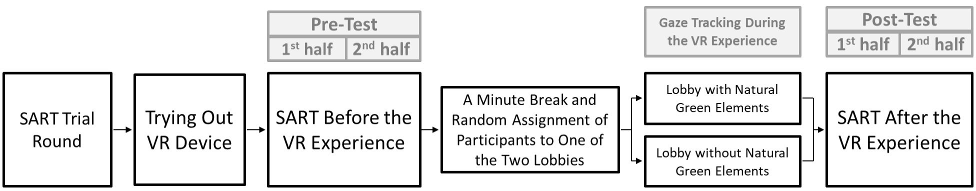

Fig. 3: The procedure that participants completed to successfully participate in the experiment

Following the orientation tasks and the pre-immersion SART test, researchers randomly assigned each participant to walk through one of the two IVREs, as illustrated in Figure 3. Four SteamVR (SV) base stations were used to detect the participants' movements. The participants put on the VR Headset and walked through their assigned IVRE from the entrance doors to the elevators. As the participants physically moved their virtual location changed relative to their starting point.

Participants began the experiment by clicking a key on the VR controllers. They had to push the same key when they got to the elevator to complete the task. The participants were asked to walk at their normal walking speed, not rushing or pausing during the experience, and without direct interaction with the vegetation or the lobby. Modeling the lobby as a virtual environment, rather than changing a real lobby, made it easier for researchers to test various prototypes at a lower cost (SAEDI & BOONE 2018).

3 Results

The data were analyzed to see: First, if there was a significant difference in SFV and FFV, as recorded by the SART tests, among the participants of the two groups. Second, did the vegetation garner more attention than other elements for the participants that showed the greatest improvement in SART scores? Third, if there was a relationship between the amount of visual attention paid to vegetation by an individual and their FSV and FFV?

3.1 Sustained Attention to Response Task (SART)

164 out 182 participants successfully completed the experiment. Following the same SART setup as the SAEDI & RICE (2022) and SAEDI et al. (2021), data obtained for the experiment was analyzed in four different ways. The standard deviation in response time was calculated to measure the overall response variability. The FFV in respond time was calculated to measure changes in the cortical attentional control. The SFV in responding over the course of the task was calculated to track changes in sub-cortical arousal. Finally, the mean response time for the participants in both groups was calculated separately to make sure that one groups was not inherently faster or slower than the other to determine if the results were comparable.

Table 1: The Mean (M) ± Standard Error (SE) for Response Time and Standard Deviation of Response Time provided in Seconds. Median (M.E.) and Interquartile Range (IQR) are Presented for the fast frequency and slow frequency variability on the sustained attention to response task SART test in power.

	Pre-Test								Post-Test							
	1st Half				2nd Half				1st Half				2nd Half			
	M.E.	IQR	M	S.E.	M.E.	IQR	M	S.E.	M.E.	IQR	M	S.E.	M.E.	IQR	M	S.E.
Standard Deviation of response time																
Lobby with Natural Elements			95.20	4.33			102.36	4.90			89.54	3.67			94.14	3.99
Lobby without Natural Elements			92.48	3.76			106.88	4.55			103.11	5.01			114.13	5.32
Fast frequecny variability																
Lobby with Natural Elements	127,886	121,693			122,839	130,020			114,859	127,934			137,836	119,009		
Lobby without Natural Elements	131,684	124,522			146,138	162,641			136,987	142,638			182,348	188,746		
Slow frequency variability																
Lobby with Natural Elements	137.13	168.14							117.80	152.78						
Lobby without Natural Elements	151.11	262.2							193.26	242.65						
Mean response time																
Lobby with Natural Elements			561.71	17.23			521.16	18.33			523.37	18.51			517.80	20.01
Lobby without Natural Elements			539.53	16.34			519.92	18.63			518.72	20.10			499.88	18.13

The SART response times were converted into time-series data, trended, and divided into seven segments to calculate the FFV for each participant according to the method used by JOHNSON and her colleagues in 2007. Every segment consisted of seventy-five data points with fifty points overlapping. These data points were then hamming-windowed and zero-padded for a cumulative length of four hundred and fifty points to assess possible improvements in sustained attention level for the standard deviation to response time and the FFV for the two halves of the pre-test and the two halves of the post-test. The slow frequency variability results were not divided into two halves, and both were analyzed for the full pre-test and the entire post-test sections. The FFV and SFV data had non-normal distribution. Hence, the Mann-Whitney U-test was used to measure differences between FFV and SFV for the two groups. In addition, Friedman`s analysis was employed to determine variance to measure differences in performance among the same group's participants. The mean response time and the standard deviation to response time were analyzed by analysis of variance and the pairwise adjusted Bonferroni comparison, in that this data had a normal distribution. The mean response time comparison between the two groups showed that there was no significant difference. This confirmed that members of one group did not, as a group, react more quickly to numbers appearing on the screen [F (1,164) = 0.10, p = 0.759]; therefore, the results obtained from the two groups were comparable (JOHNSON et al. 2007).

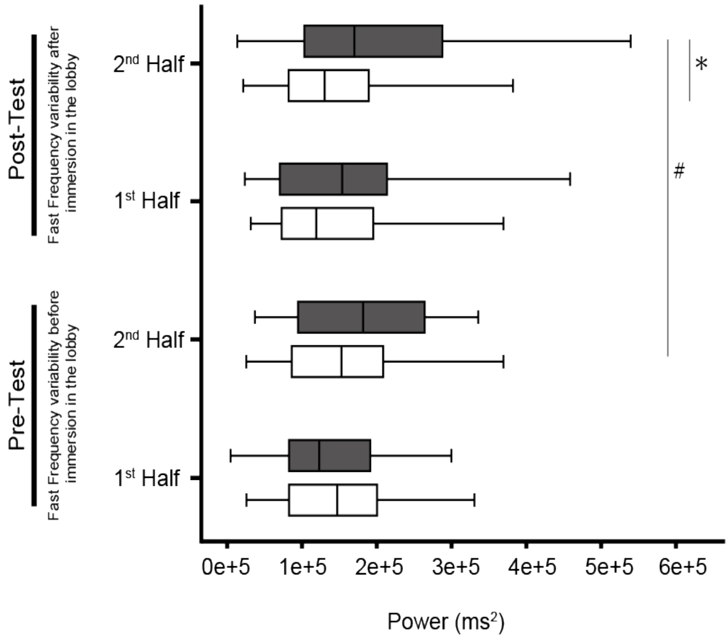

Fig. 4: Boxplot of the median and variance of FFV (reported as power). Participants experienced the lobby without vegetation (gray boxes) or with vegetation (white boxes). Data shown for the 1st and 2nd half of the pre-test, and the 1st and 2nd half of the post-test. The asterisk indicates a significant difference between participants exploring the lobby with and without vegetation (p = 0.014). The hash sign indicates a significant increase in variability for participants experiencing the lobby with no vegetation in the 2nd half of the SART task from pre-test to post-test (p= 0.041).

All participants responded faster in the post-test then the pre-test [F = (1, 164) = 5.33, p = 0.021, r = 0.19]. They also responded faster in the second half of the pre-test and second half of the post-test in comparison with the first half of the pre-test and the first half of the post-test, respectively [F = (1,164) = 14.88, p<0.001, r = 0.35]. This response speed difference can be associated with experience gained from the pre-test (LEE et al. 2015).

For the individuals experiencing the lobby with no vegetation this experiment showed that the FFV declined over the course of the experiment [Lobby with no vegetation, x2 (3) = 29.05, p< 0.001; Lobby with vegetation, x2(3) = 2.11, p = 0.533]. The results also, as illustrated in

Figure 4, revealed there was more significant FFV between the two halves of the post-test in comparison with the two halves of the pre-test [z = –1.75, p = 0.034, r = –0.14]. In addition, there was no significant difference between the members of the two groups' FFV for the two halves of the pre-test [1st half, U = 2450, p = 0.376, r = –0.03, 2nd half, U = 2322, p = 0.165, r = –0.08] nor the first half of the post-test. On the contrary, there was a significant difference in FFV for the second half of the post-test between the members of the two groups. This result is marked by the asterisk in Figure 4. These results indicated that after the VR experience in the lobby without vegetation, participants` attention control was significantly less than that of participants who experienced the lobby with vegetation [U = 1989, p = 0.013, r = 0.18].

According to the data illustrated in Figure 4, between groups comparisons from the SART verified no significant difference between the members of the two groups' attention level prior to walking through one of the two lobbies [U = 2231, p = 0.148, r = –0.12]. After physically walking through the VR lobby participants who encountered the vegetations during the experience demonstrated significantly lower SFV then those who experienced the lobby with no vegetation [U = 1971, p = 0.008, r = –0.21]. After a with-in group comparison, no significant changes were observed in the SFV among the participants experiencing the lobby with vegetation, (z = –1.37, p= 0.090, r = –0.09). Or the participants experiencing the Lobby without vegetation, (z = –0.74, p= 0.232, r = –0.05].

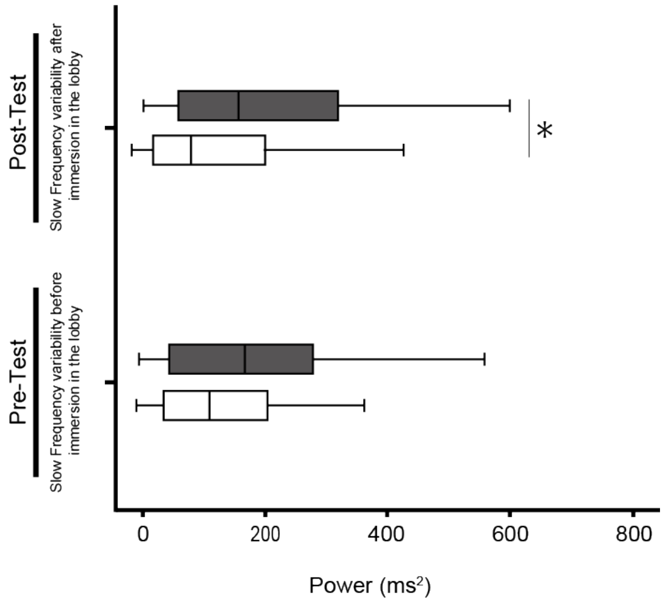

Fig. 5: Boxplot of the median and variance of changes SFV. Results for performance at pre-test and post-test obtained from participants who experienced the lobby without natural/green elements (black boxes) and the lobby with natural/green elements (white boxes). The asterisk indicates a significant difference between participants who walked through the lobby with vegetation compared to those who experienced the lobby with no vegetation at post-test (p = 0.008). No meaningful difference was observed at pre-test (p = 0.143).

Standard deviation analysis revealed a more consistent response time pattern from, individuals who experience the lobby with vegetation and therefore a higher level of sustained attention (Table 1). Also, the results indicated that the higher level of sustained attention was maintained by individuals who experience the lobby with vegetation $F(1, 164) = 12.56$, $p < .001$. Data also recorded no significant difference in the baseline for individuals in the two groups $F(1, 164) = 0.00$, $p = 0.939$, $r = 0.00$.

There was a significant difference in the performance of individuals after experiencing different lobby versions $F(1,164) = 5.44$, $p = 0.031$, $r = 0.18$. As reflected in Figure 5, individuals who experienced the lobby with vegetation demonstrated less SFV $F(1, 164) = 5.00$, $p = 0.023$, $r = 0.18$. A significant SFV increase was seen in participants in the group that experienced the lobby with no vegetation $F(1, 164) = 7.59$, $p = 0.007$, $r = 0.27$.

The FFVs measured for both halves of the pre-test and both half of the post-test demonstrated that both groups' response time variability, as indicated in Figure 5, was lower on the first half of the pre-test as compared to the second half of the pre-test. Similar interpretation was valid for the first half of the post-test compared to the second half of the post-test $F(1,164) = 4.57$, $p = 0.041$.

3.2 Gaze Tracking

The generated heatmaps (Figure 2) demonstrated that for the lobby with the vegetation, participants' visual attention was mainly clustered in regions with vegetation. For the lobby with no greenery, the visual attention clusters mainly formed around the pathways to the elevator, the elevators' doors, the unit numbers on the walls, and the physical corners in the space.

Results from the SART indicated that the participants in the lobby with vegetation demonstrated significantly lower SFV and FFV compared with the participants of the other group. The only difference between the two version of the lobby was the presence of vegetation in one version. So, the SART results could be attributed to that difference. But it could be argued that maybe the group of participants who experience the lobby with vegetation inherently favored vegetation.

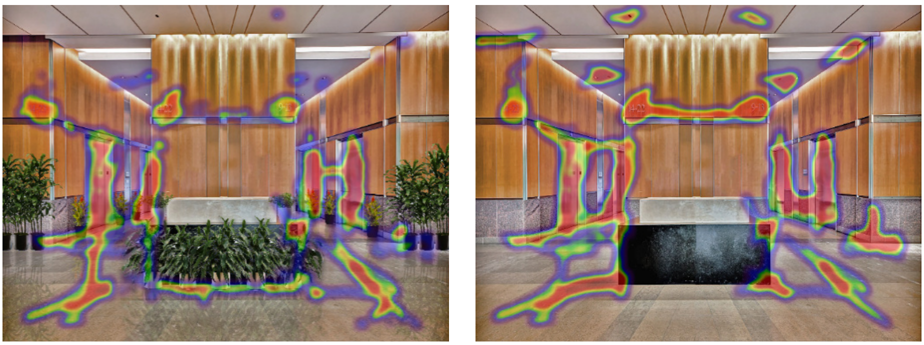

Fig. 6: Snapshots of the two cumulative heatmaps for the study site. The point cloud associated with the vegetation was excluded.

To address the concern, data in the point cloud associated with visual attention to vegetation was separated from the rest of the dataset. The new point cloud was then used to generate two new heatmaps (Figure 6) for the two different version of the lobby using the same process explained in section 2.3.2.

Figure 6 shows no significant difference in the fixation location and fixation duration during the VR experience. In the absence of vegetation all participants focused most of the visual attention to similar elements or parts of the lobby. These findings allowed researchers to compare the heatmaps with higher levels of confidence. Also, Data obtained from the group experiencing the lobby with vegetation revealed a strong reverse correlation between the duration of visual contact with nature and less SFV and FFV.

To confirm that the extensive amount of visual attention received by the vegetation was responsible for the significantly less SFV and FFV and the amount of attention was not associated with the larger volume that vegetation occupied in the space another correlational analysis was performed. The point cloud used to generate Figure 6 was used to see if there was a correlation between the other elements in the space that received the significant amount of visual attention from the participants not considering the vegetation and no correlation was observed. This outcome was also true for the correlational analysis between the elements in the lobby with no vegetation and individuals' SFV and FFV.

4 Discussion

This research corroborates the findings from previous established studies that suggest that presence in nature or visual interaction with nature has restorative effects and can help individuals to recover from mental fatigue (KAPLAN 2001, ABKAR et al. 2010, SAEDI & RICE 2019, SAEDI & RICE 2021). These outcomes of the research are also in line with more recent studies that demonstrate utilizing vegetation in the interior design of a space, such as in hospitals (TALBOT & KAPLAN 1991, WELLS & EVAN 2003) and offices (LARSEN et al. 1998, LOHR et al. 1996, RICH 2007, SHIBATA & SUZUKI 2002, 2004) has similar restorative effects.

In this research, the SART score before experiencing one of the two IVREs were not significantly different between the participants of the two groups. This experiment took place at the end of workdays and the similar performance demonstrated by participants at baseline might be related to the fact that most of the individuals were cognitively exhausted and depleted their mental resources to fulfill their responsibilities.

These findings further explain the outcome of other studies such as LEE et al. (2015), SAEDI & RICE (2019, 2022), CHAN et al. (2021), and SAEDI et al. (2021). In those studies individuals who experienced greenery in an interior environment demonstrated significant improvement in their cognitive performance. Such improvement was not recorded among those who experienced an interior environment without greenery.

In this research, the heatmap of the lobby with vegetation revealed that an extensive amount of visual attention was devoted to vegetation. Previous studies suggest that vegetation is fascinating for most individuals and attract indirect attention which allows direct attention to replenish (KAPLAN & KAPLAN 1989, SAEDI & RICE 2019, CHAN et al. 2021). The heatmap of the lobby with no vegetation showed that most of the visual attention was given to the parts of the space that would support individuals getting from the entrance to the elevator and avoiding injury by sharp corners. In contrast with the lobby with vegetation, paying visual attention to these elements requires involvement of an individual's direct attention. Therefore, participants direct attention does not get a chance to recover.

Based on the outcomes of this research, it can be inferred that the non-restorative characteristics of a space may be due to the absence of not only "green" but also inherently intriguing characteristics or features that can promote fixation locations and extend fixation duration and therefore encourage an individuals' involuntary attention. As a result, voluntary attention dominates. As the attention restoration theory (KAPLAN & KAPLAN 1989) suggests, this voluntary involvement with an environment consumes mental resources and does not allow individuals to recover and replenish. Also, the participants' visual attention patterns were analyzed to make sure that they were comparable. However, there is a possibility that a large number of participants in the lobby with vegetation were inherently more intrigued by greenery and therefore, they paid more visual attention to vegetation. Although from the statistical point of view the probability for such an event is unlikely, it would be helpful to take such inherent affinity for nature into account in the future studies.

So far, research on the impact on attention restoration of interacting with nature or vegetation has shown significant improvements in the individuals' attention level. This impact has been observed for durations of interaction from a few minutes to hours and days (BERTO 2005, BRATMAN et al. 2015). The outcome of this study expanded on the existing literature by suggesting that such an impact can occur in a much shorter timeframe.

The use of IVRE in studying the impact on attention restoration of interaction with nature is expanding (BERMAN et al. 2008, BERTO 2005, BEILENSON 2018). Recent studies such as LI et al. (2020) compared the results of experiencing an environment both in real life and IVRE reveal and observed no significant difference between them (JIANG et al. 2021, YIN et al. 2019, KULIGA et al. 2015). Above that, studies have demonstrated that under the same circumstance, the impact of interaction with vegetation in virtual environments are less pronounced compared to interaction with those elements in real life (BANFI et al. 2018).

Thus, it can be inferred that if the significant restorative effects were observed in IVRE, the restorative could be more prominent in a real-life experiment. Nevertheless, there are still questions about how similar a real-life experience of nature is to a IVRE experience of nature? Since this study took place in an IVRE results similar to the real world are expected but not guaranteed.

5 Conclusion

The outcome of this research suggests that adding vegetation to the design of an interior space has the potential to change the way in which individuals visually interact with that environment. This change in visual interaction may be a major contributing factor to the restorative effect of designed environments with vegetation. A shift in visual fixation location and fixation duration to green elements significantly impacts the level of restorative effect. Individuals who looked at green elements less often and for less duration demonstrated a significantly less restorative benefits. These results indicate that the specific characteristics of green elements and how they have the potential to attract and sustain attention may be very important. In addition, result show that individuals can benefit from the positive impacts of interacting in a VR environment with elements resembling natural vegetation and this benefit can occur even if the interaction is of a short duration.

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