The nature gaze: eye tracking experiment reveals wellbeing benefits derived visual attention toward elements of nature

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The nature gaze: Eye tracking experiment reveals wellbeing benefits derived from directing visual attention toward elements of nature

Abstract

1. The urban lifestyle has a profound effect on mental health, contributing significantly to the challenges faced by people who reside in urban areas. Growing empirical evidence underscores the potential of nature to alleviate these mental health burdens. However, we still lack understanding on which specific natural elements provide these benefits.

2. Using eye-tracking technology, we experimentally explored the relationships between intentional visual attention to natural (green) and human-made (grey) elements in urban areas and their association with wellbeing measures. Participants took a 45-minute outdoor walk that simulates a walk to and from work, in which we examined pre and post measures of cognition, affect, anxiety, and perceived restorativeness. Participants were prompted to direct their attention to green, grey, or a mixture of both elements. By analyzing participants' eye movements and patterns, we determined adherence to experimental conditions and related visual attention to natural elements.

3. The experimental groups instructed to direct their visual attention to green, grey, or a mix of both infrastructures exhibited differences in negative and positive affect, anxiety, and perceived restorativeness, but not in cognition after a walk in an urban environment.

4. The percentage of time spent viewing natural elements showed that people who focused more on green features reported a decrease in anxiety and higher perceived restorativeness. In contrast, those who spent more time viewing gray elements reported increased anxiety and lowered perceived restorativeness. The percentage of time viewing natural elements was not linked to affect

or cognition. Viewing trees showed the strongest association with wellbeing measures compared to other natural elements.

5. Together, our results indicate that a simple behavior change (directing visual attention to elements of nature instead of gray elements) can produce mental health benefits in the form of reducing anxiety and perceived restoration for people in urban areas. Thus, efforts to integrate nature, especially trees, in urban areas and promoting city dwellers to visually interact with it during their daily routine can improve mental issues associated with urban lifestyle.

Introduction

Cities have become thriving centers of economic growth, innovation and knowledge production, but these novel ecosystems (Kowarik 2011) can also have significant implications for the health and wellbeing of humans (Bertram & Rehdanz, 2015; Takahashi et al., 2021). Myriad studies have linked urban lifestyles with chronic stress and mental fatigue that can lead to noncommunicable diseases such as depression and anxiety (Lederbogen et al., 2011; Wang, 2004). Urbanization is therefore emerging as a major contemporary global challenge with troubling implications for human health, but nature has shown remarkable promise for addressing this challenge (Colléony & Shwartz, 2019). Mounting empirical evidence underscores the mental health benefits of nature interaction, including psychological restoration, stress reduction and improved mood (Hartig et al., 2003; Roberts et al., 2019; Yao et al., 2021). Even a brief interaction with nature can enhance happiness and reduce rumination (Bratman et al., 2015). Exposure to natural settings can also boost cognitive performance and attention restoration, suggesting a positive impact on cognitive function and mental clarity (Berman et al., 2008; Tennessen and Cimprich, 1995; Kaplan and Kaplan, 1989). Therefore, interaction with nature in urban environments has received considerable attention in research, as it can buffer against the mental burdens of city living (Bai et al., 2012; de Vries et al., 2016; Lenzi & Perucca, 2020; White et al., 2013). However, the relationship between nature and wellbeing is complex, with research often addressing nature as a ‘black box’ where the underlying mechanisms remain largely unexplored (Colléony & Shwartz 2019).

A typical approach to studying nature and wellbeing involves comparing wellbeing measures before and after nature visits or walks, contrasting these with experiences in urban settings (e.g., Berman et al., 2012; Bratman, et al., 2015; Elsadek et al., 2019; Hartig et al., 2003). Although these studies indicate a measurable difference between walking in natural and urban settings, they do not address what aspects of the experience contribute to these benefits. For example, multiple sensory aspects are involved in experiencing or interacting with nature, such as seeing, hearing, smelling, and touching (Gaston et al., 2018). A recent experiment has demonstrated the effect these varied interactions in natural settings can have on positive affect (Colléony et al., 2021). Studies of the psychological benefits of viewing nature using indoor experiments have indicated that visual attention to nature is a primary avenue for benefits (Jo et al., 2019). Direct visual contact with natural elements is likely a key factor in deriving wellbeing benefits derived from nature, such as attention restoration from cognitive fatigue (Grinde & Patil, 2009; Varkovetski, 2015). But real-life knowledge on how visual attention to different nature elements (e.g., trees, flowers) impacts psychological benefits is still scarce. This gap extends to understanding the needed ‘dose’ of nature and the type of nature interactions that can optimize benefits (Meredith et al., 2020; Richardson et al., 2021). This information can guide practitioners in using natural elements as building blocks to design healthier environments (Colléony & Shwartz 2019; Hartig et al., 1996) and eye tracking technology can help establish this knowledgebase.

Eye-tracking research offers insights into human cognition and attention in various fields, including psychology, marketing, and user interface design (Meißner & Oll, 2019) and can be used to understand how individuals perceive and value natural environments (e.g., Cottet et al., 2018). Eye-tracking techniques come in various forms, such as desktop, virtual reality (VR), and mobile systems, each offering unique advantages and limitations. For example, desktop eye tracking offers precise measurements in controlled settings, while VR eye tracking enables immersive studies, and mobile tracking captures real-world interactions, but has calibration and comfort challenges (Holmqvist et al., 2011; Hutton, 2019). Each method is tailored for specific research needs that balance control, realism, and mobility. Furthermore, eye tracking experiments can utilize various indicators, chosen based on study objectives, to thoroughly analyze visual attention and cognitive processes. Fixations and saccades are key indicators, identifying points of focus and shifts between them, that uncover engaging aspects of landscapes and cognitive engagement. Fixations are particularly effective in visual attention studies, offering direct insights into how visual intake of environmental elements impact psychological responses (e.g., (Duchowski, 2007; Holmqvist et al., 2011). Fixations and saccades can also be used to generate gaze heatmaps that visually represent areas with high gaze concentration, highlighting regions of interest. Other indicators can reveal additional unique aspects of eye movement behavior. For instance, Time to First Fixation (TTFF) can be used for assessing initial visual attention, Scanpaths for exploring fixation and saccade sequences, blink rates and pupillary light reflexes for insights into eye health and attention dynamics (Dewhurst et al., 2018; Simonetti & Bigne, 2022; Zou et al., 2023).

While mobile eye tracking studies in outdoor environments are increasing, they are still somewhat uncommon, even though essential gaze features are apparent when moving (Uttley et al., 2018; Jovancevic-Misic & Hayhoe, 2009). Studies that have allowed participants more active movement while viewing images have found differences between static and active viewing (e.g., Foulsham et al., 2011), where nearly all features of gazing differ between active and static viewing conditions (Haskins et al., 2020). Studies that have used this technology in mobile outdoor settings generally are completed with small sample sizes (less than 50 participants) and a relatively short walk duration (less than 20 minutes; e.g., Gholami et al., 2021; Simpson et al., 2019; Trivic, 2023). In these studies, researchers have found that, when undirected, participants look at human-made structures more than natural structures (Gholami et al., 2021), and participants, especially when elderly, look at the ground, ground level more than they look up (Simpson et al., 2019; Trivic, 2023).

To date, most research aiming to explore how individuals perceive and value landscapes or natural environments has used eye tracking indoors on photographs or in still settings. These studies have found that the assessed visual quality of landscapes relates to landscape heterogeneity (de la Fuente de Val et al., 2006), degree of openness (Dupont et al., 2014), and fixation duration on greenery (Kerimova et al., 2022). Stationary studies using images or photos have also examined the associations between visual assessments of landscapes and restorative assessments of those landscapes. In these studies, landscape elements such as grass, trees, shrubs, and water have been associated with positive restorative benefits, while built elements have been negatively associated with restoration (Liu et al., 2022; Nordh et al., 2013). There are also significant positive relationships between landscape preference, perceived restorativeness, and fixation percentage (Wu et al., 2021). Valtchanov & Ellard (2015) found that the restorative aspects of natural environments associated with visual properties of a scene may work through multiple mechanisms where environments may only offer cognitive or affective benefits. Finally, Cottet et al. (2018) found that specific natural landscape elements in urban settings may be important for wellbeing benefits. However, there is a gap in understanding whether these patterns remain in real-life outdoor environments in sedentary or active situations.

Here, we aimed to explore how visual attention to green elements may be associated with positive and negative affect, anxiety, and attention. Using mobile outdoor eye tracking technology, we conducted a controlled experiment, comparing three groups of participants who took the same 45-minute walk that simulates a daily urban walk to/from work, for instance. Unlike previous studies that focused on undirected visual attention during walks (e.g., Gholami et al., 2021; Rupi & Krizek, 2019; Simpson et al., 2019; Trivic, 2023) our approach involved all participants experiencing the same route but with a unique element: directed visual attention. Participants were instructed to concentrate their gaze on specific elements, green (vegetation), grey (man-made), or a combination of both, and made stops at ten strategically chosen points that exemplified these elements (Fig. 1). This variation allows to: (1) compare how directed visual attention influences the nature experience of the same walk, including visual intake of nature or non-natural elements, and wellbeing measures such as cognition, affect, anxiety, and restorativeness; (2) how the percentage of time spent directing visual attention toward nature or grey infrastructure is related to differences in cognition, affect, anxiety, and restorativeness using areas of interest while participants are stopped; and, (3) how the percentage of time spent directing visual attention toward nature or grey infrastructure is related to differences in cognition, affect, anxiety, and restorativeness using areas of interest while walking including to what extent different elements of nature (e.g., trees and lawns) are associated with differences in cognition, affect, anxiety, and restorativeness. We expected that a greater percentage of time viewing green elements would be associated with increased cognitive function, improvement in affective measures, reduced anxiety, and greater perceived restorativeness.

---------[Figure 1 about here]----------

Materials and Methods

Participants and Experimental Procedure

Over nine months, 117 adults (65 women, mean age = 26.1) without neurological or psychiatric disorders were recruited to participate in the study. They participated in a guided walk wearing eye tracking glasses to monitor their visual engagement on and around the campus of the Technion – Israel Institute of Technology's in Haifa, Israel (Fig. 2). Before the walk, participants responded to a battery of psychocognitive measures of affect, anxiety, and attention (Fig. 1). Upon completion, participants were fitted with Tobii Pro 2 eye tracking glasses and brief instructions were given to limit their head movements and look directly through the glasses as much as possible throughout the walk. A research assistant guided participants on a 45-minute walk (Bratman, Hamilton, et al., 2015; Yao et al., 2021) from the campus laboratory to the adjacent neighborhood and back, in which we integrated ten stopping points per participant (Fig. 2). After the walk, the participants had their eye tracking equipment removed and then repeated the same set of psychocognitive measures, also including an additional scale that evaluated the perceived restorativeness of the walk (Fig. 1). Together, this procedure took about 70 minutes and upon completion the participants were compensated 50NIS (~$15) for their time.

Individuals were randomly sorted into one of three experimental groups (39 participants per group), which differ in the level of green elements at the stopping points, and the instructions provided. Thus, they walked the same route but were stopped at different points along the way, but the same number of points overall (Fig. 1). Participants in the 'green' group stopped at points dominated by vegetation and were instructed to direct their attention to natural elements (Fig. 3a; Fig. S1 in Supporting Information). Participants in the 'grey' group stopped at points dominated by human-made infrastructure such as buildings, pavement, and roads, and were asked to direct their attention to man-made elements (Fig. 3b; Fig. S1). Participants in the 'mixed' group stopped at points with mixed green and grey elements and were instructed to focus on how nature and built elements are mixed (Fig. 3c; Fig. S1). These directions were administered in Hebrew (see Text S1 in Supporting Information for an English translation). Five participants were disqualified (one participant voluntarily quit halfway through, one admitted that they did not qualify based on the consent form, and three were discounted because of a fundamental error with either the software or hardware, resulting in limited or no data).

---------[Figures 2 & 3 about here]----------

Data Measures

The Tobii Pro 2 eye-tracking glasses (Tobii AB, 2015) were used to track eye movements with six inward-facing IR cameras and, using a single forward-facing camera to record the scene in front of the participant. The eye movement recordings were then overlaid on the scene recording and analyzed using the iMotions 9.x software package (iMotions, 2020). Using the eye-tracking glasses, we recorded several visual attention variables (Fig. 1). Wellbeing outcomes and demographic variables were collected in the before/after surveys (see Text S2 in Supporting Information for full versions of these measures) and control variables were collected from secondary resources (Fig. 1).

Eye-tracking Measures

In situ eye tracking is a relatively novel method for examining individuals' sight mechanisms, their interactions with environments, and how visual perceptions relate to thoughts, feelings, and reactions to environmental stimuli. This technique uses eye-facing infrared (IR) cameras to track eye movements, reflecting individuals' visual patterns when processing information (Koop & Johnson, 2011). The two most common metrics in eye tracking are saccades (lateral eye movements) and fixations (pauses in eye movement). Fixations occur when the eye stops moving and focuses on a stimulus, with a cluster of fixations around an object termed a gaze or dwell (iMotions, 2020b). Observers fixate on items of interest, and analyzing gaze/dwell patterns helps understand social information processing abilities (Birmingham et al., 2009) and discern preferences (Glaholt et al., 2009). In our study, we focused solely on fixations as they indicate personal interests. Saccade analysis, more suited for studies of distress (like PTSD), requires a strictly controlled environment. As our goal was to evaluate the impact of gaze on green elements, we did not measure other indicators such as Time to First Fixation (TTFF) and Scanpaths, which assess different aspects of eye movement behavior, like initial visual attention and sequences of fixations and saccades.

Eye tracking data were collected at both stops and continuously as participants moved between stops. To gauge visual interest during the walk, we used two sets of indicators: one for stops and another while the participants walked. Initially, fixation clusters (gazes) around stimuli at stopping points were analyzed. We captured photographs at each stop and delineated polygons around Areas of Interest (AOIs), categorizing them as green (vegetation and bare soil), grey (man-made structures such as roads, pavements, buildings, and vehicles), and mixed (areas with indistinct separation between green and grey elements). The participants' eye movements were then superimposed onto these photographs, allowing us to quantify the number of fixations and the duration of dwell time on these AOIs. Detailing AOIs into more specific green or grey elements was challenging in our outdoor study, as participants varied in their physical positions, we therefore needed to individually adjust AOIs, preventing extremely precise classification of each element in our AOI digitization. Utilizing iMotions' gaze mapping algorithm, heatmaps were generated to visually represent fixations and gazes on the photographs, illustrating the intensity of interest in specific AOIs based on the total time spent dwelling in them (iMotions, 2020b). For analyzing the stopping points, we calculated the sum of the fixation durations in milliseconds (ms) while participants gazed at green or grey AOIs. We then summed the total time of fixations and calculated the percentage of time for fixations on green and grey elements. This percentage variable was used in further analyses related to wellbeing measures. The mixed category was omitted from this analysis due to the difficulty in distinctly categorizing visual attention towards either of the two categories.

Conducting AOI analysis for the mobile phase of the walk posed a significant challenge, as it involved digitizing AOIs for every segment of the walk for each participant. Consequently, fixations recorded between stops were manually coded by a researcher using iMotions. This process involved reviewing every 15th fixation and assigning it to specific elements such as trees, bushes, lawns, flowers, people, buildings, vehicles, animals, etc., based on their appearance in the video (see Fig. S2 for an example of this coding). The choice of the 15th fixation was a practical compromise, balancing sampling effort with feasibility, given that the ideal scenario of using every fixation was constrained by time limitations. When a fixation occurred on an area encompassing both natural and man-made elements, it was classified as 'mixed' (see Figure S2) and excluded from the analysis. Thus, in the mobile phase, we summed the total fixation time, and calculated the percentage of time spent looking towards both green and grey categories, akin to the AOI analysis at stopping points, and also towards each of the four natural elements (trees, bushes, lawns, and flowers).

The Tobii Pro Glasses 2 and similar eye-tracking devices struggle in bright sunlight due to interference from ambient IR radiation and reduced contrast for effective pupil detection. These glasses are optimized for reflected light capture, and Tobii recommends their use indoors with controlled lighting and minimal head movement. To mitigate the effects of sunlight, our experiment was conducted in the morning and evening with shadier conditions. Participants were also fitted with a baseball cap (Simpson et al., 2019) to reduce light interference, and were instructed to keep their heads as steady as possible. Despite these challenges, the glasses successfully recorded the majority of eye movements, suitable for analysis with iMotions. Participants with more than 66% of captured eye movements were included in the analyses. At the stopping points, where the participants were stationary, the recording quality was mostly adequate. The majority of recording issues occurred during movement. The random assignment of participants to the experimental conditions should ensure that these limitations do not impact the comparison between the experimental conditions. However, to account for the challenges of using eye-tracking technology outdoors and other variability in total fixation time between participants, we standardized the total fixation time towards each category or natural element. In all eye tracking analyses, we used the percentage of total fixation time spent on specific categories or elements. This metric was calculated by dividing the total time fixating on a specific category by the total fixation time for each participant. We separately calculated this percentage for the green and grey categories in the stopping point AOI analysis and both categories and individual elements (e.g., trees and flowers) in the mobile 15th fixation analysis.

Finally, we assessed whether the percentage of time spent looking at green or grey elements, as determined by eye tracking, aligned with the experimental groups (i.e., condition). For this purpose, we conducted Kruskal-Wallis tests. The Kruskal-Wallis test, a nonparametric equivalent to a one-way ANOVA, is ideal when normality assumptions are not met, as in the case of percentages. We ran four separate tests, with the condition as the independent variable and the percentage of time spent looking at green and grey elements, both while stopped and while walking, as dependent variables. This analysis revealed significant differences in the time spent looking at green or grey elements between the three experimental groups during both the stops and the entire walk (Fig. 4). Therefore, the time that participants spent looking at the green or grey elements corresponded to their assigned treatment conditions. Participants in the green group focused more on green elements, whereas those in the grey group paid more attention to grey elements. The results of the mixed group conditions were intermediate, as expected.

---------[Figure 4 about here]----------

Wellbeing outcome, demographics, and control variables

Affective measures were measured using a questionnaire that included assessments of anxiety, positive affect, and negative affect (PANAS – Positive and Negative Affect Scale). Anxiety was assessed using the State-Trait Anxiety Inventory (STAI; (Elsadek et al., 2019; Spielberger et al., 1983). This survey consists of 40 items that assess both state anxiety (momentary judgment) and trait anxiety (general levels of anxiety), where each is composed of twenty questions. Questions are asked on a 4-point scale, where for state anxiety, participants are asked to assess the intensity of their current feelings from (1) not at all, to (4) very much so, and for trait anxiety, to assess the intensity of their feelings in general from (1) almost never to (4) almost always. Positive and negative affect were evaluated using the Positive and Negative Affect Scale (PANAS; (Berman et al., 2012; Watson et al., 1988). This survey consists of 20 items that assess both positive and negative affect, with 10 items for each. Questions are asked on a 5-point scale, where participants are asked to assess the degree to which they felt the items describe their current state from (1) very slightly, or not at all, to (5) extremely. Affective measures were taken before and after the walk. For each measure collected, STAI, positive PANAS and negative PANAS, a difference in before and after scores was calculated. We used the official Hebrew translation of each measure.

Participants were also given the Necker Cube Change Pattern Change Detection Task (NCPCT) cognitive task to measure cognitive ability related to attention. For the NCPCT task, which measures directed attention, participants used a computer to click every time they perceived a change in the cube's orientation. Participants are instructed to focus on holding one pattern, and therefore, a change is attributed to attentional fatigue (Hartig et al., 2003; Kaplan, 1995). Cognitive measures are not a measure of overall cognitive ability, but rather a measure of attention restoration related to cognitive function. Participants were introduced to the task, given written instructions, and allowed to practice for 10 seconds. The participants then completed the task in two rounds of 30-seconds each with the number of clicks indicating attention. A second cognitive task consisting of the change blindness exercise was administered to all participants. The data for this task were not viable due to an error in administering this task and not used in analyses. The NCPCT cognitive measure was assessed before and after the walk, and similarly to affective measures, a difference was calculated before and after scores.

In addition to affective and cognitive measures, participants were asked about their perceived restorativeness of the walk using the Perceived Restorativeness Scale (PRS-11). The PRS-11 was developed by Pasini et al., (2014) as a shorter alternative to the PRS developed by Hartig et al., (1997). The PRS-11 comprises 11 items that deal with fascination, being away, coherence, and scope. Participants are asked to rank their agreement with items on a 5-point scale from (1) not at all to (5) very much.

Participants were also asked to indicate their connection to nature using the nature relatedness scale (NR-6). The NR-6 was developed by Nisbet and Zelenski (2013) as a shorter alternative to the NR developed by Nisbet et al., (2009). The NR-6 consists of six items in which individuals indicate on a 5-point bipolar scale how much they agree with each statement from (1) strongly disagree to (5) strongly agree. Demographic questions were also asked, including age, gender, childhood residence size (medium/large city, small town, kibbutz), and current residence size (medium/large city, small town, kibbutz). Additional environmental control variables, including air quality (measured using the Breezometer Air Quality Index or BAQI), temperature, relative humidity, visibility, and cloud cover (%), were collected for each participant at the time of their walk. These measurements were obtained while participants completed the before questionnaire from the Israel Meteorological Service Station at the Technion, which records these variables hourly (more details can be found at (IMS, 2023)).

Data Analysis

Statistical analyses were performed in RStudio (version 1.1.456; R Core Team, 2018). Preliminary data analysis confirmed that there were no significant differences between groups based on control variables (i.e., environmental conditions) and latent variables were combined into an index after determining alpha coefficients were acceptable (>0.75 for all scales; Text S3 in Supporting Information). We performed three types of analysis: (1) analysis of changes in wellbeing outcomes before and after interventions (without eye-tracking); (2) analysis of how differences in the percentage of fixations time on green and grey elements at stops were associated with affective, cognitive, and restorative measures (AOI analysis at stops); and (3) analysis of how the percentage of fixations time on green and grey elements, as well as specific natural elements (trees, flowers, bushes, and lawn) throughout the walk were associated with affective, cognitive, and restorativeness measures.

For the first set of analyses, mixed models for repeated measures were run with individual as a random effect to assess differences in PANAS, NCPCT, and STAI (state) before and after the walk given group assignment (green, grey, or mixed condition). The interaction of time (before/after) and condition (green, grey, and mixed) was used as an independent variable, along with individual (random effect) with all control variables listed in Fig. 1, including demographic and environmental variables. This results in four separate models, one for each dependent variable: PANAS (positive and negative), NCPCT, and STAI state. A linear model for perceived restorativeness was also run, which is a measure only taken after the experiment, based on group assignment with the same variables mentioned in the previous analysis and no random effect. Estimated marginal means were calculated to examine differences in dependent variables between groups and differences before and after the experiment.

In the second set of analyses, we built 10 linear models to explore the variables that influence the changes in PANAS (positive and negative), NCPCT, STAI state, and perceived restorativeness during stops in areas of interest (AOIs). We calculated differences in the first four response variables (measured before and after) by subtracting the pre-walk scores from post-walk scores for each participant. The percentage of time gazing at green or grey elements while stopped was used as independent variables, along with all control demographic and environmental variables (Fig. 1). Due to the high correlations found between the percentage of time looking at green and grey elements (Fig. S3a & Fig. S3b), separate model sets were built for each variable. This resulted in two model sets per dependent variable (changes in PANAS (positive and negative), changes in NCPCT, changes in STAI state, and perceived restorativeness). For each model set, we used forward stepwise model selection to create a set of candidate models starting with the null and separate models for each variable. Variables from the AIC top-performing model were propagated to the next step in an iterative process until a final AIC top-performing model was identified (Venables & Ripley, 2002; Burnham & Anderson, 2004).

In our final set of analyses, focusing on the walking phase, we built 15 linear models to explore how the percentage of time spent fixating on green or grey elements, and specific natural elements, affected changes in PANAS (positive and negative), changes in NCPCT, changes in STAI state, and perceived restorativeness. The same methods used in the second analysis were used here for the walking phase data. Due to significant correlations among independent eye tracking variables (Fig. S3a & Fig. S3b), we created three sets of separate models for overall green, overall grey, and specific natural elements (combined). This approach led to 15 linear models, assessing the relationships between the five dependent variables and the fixation percentages on green, grey and four specific natural elements (trees, bushes, lawns, and flowers), with all control variables included (Fig. 1). As in the above analysis, forward stepwise model selection was used to identify top-performing AIC models.

Correlations between all variables were tested. Correlations between control variables (demographic and environmental) and all independent variables of interest were <0.5. Correlations between percentage of time viewing specific elements (trees, lawn, bushes, and flowers) were <0.55. Correlations between percentage of time viewing green and grey elements were generally high (between 0.64 and 0.91, p<.001), and so these variables were not put in models together. Full correlation analyses with p-values can be found in supporting information (Figs. S3a & S3b). Normality assumptions and multicollinearity were checked by plotting residuals and with variance inflation factors (values between 1.03 and 1.06), respectively.

Results

The first analysis revealed that the interaction between conditions and time (i.e., before and after) was significant for positive affect and STAI state (Table 1). Participants in the green group showed marginally higher average scores in positive affect after the walk compared to their pre-walk scores (p=0.064; Fig. 5a), and these scores were higher than those of the grey and mixed groups after the walk. Both the green and mixed groups reported a decrease in negative affect after the walk, unlike the grey group, where no change was observed (Fig. 5b), but there was no difference between the groups (Table 1). No significant changes were found in NCPCT scores before and after the walk, nor between the conditions for all groups (Fig. 5c; Table 1). Pre-walk STAI state scores were significantly higher than post-walk scores for both green and mixed groups

(Fig. 5d), and there was a significant difference between the green and grey groups (Table 1). The perceived restorativeness of the green group was significantly higher than that of the mixed and grey groups, receptively (Fig. 5e). Nature relatedness correlated positively with positive affect and perceived restorativeness (Table 1). Participants who spent their childhood in large or medium cities demonstrated lower NCPCT scores.

---------[Figure 5 and Table 1 about here]----------

The percentage of time that individuals spent fixating on green or grey elements was primarily correlated with changes in STAI and perceived restorativeness (PRS; Table 2). The percentage of time spent gazing at green elements significantly reduced state anxiety, while gazing at grey elements increased it (Table 2). In all STAI models, both age and cloud cover were consistently negatively associated with STAI score differences (Table 2). Perceived restorativeness demonstrated a positive association with the percentage of time gazing at green elements and a negative correlation with percentage of time gazing at grey elements (Table 2). Nature-relatedness was positively related to perceived restorativeness (Table 2). Other control variables were either excluded in the final model after AIC model selection or found insignificant (Table 2). No significant correlations were observed between changes in PANAS (positive and negative) and NCPCT scores and the percentage of time gazing at green or grey elements. Gender was negatively correlated with changes in positive and negative affect (Tables. S1-S6). Base models for the STAI and PRS models can be found in supplementary material (Tables. S7-S10).

---------[Table 2 about here]----------

The results of the third analysis, examining fixations during the mobile phase, aligned with the results of the previous analysis around the stopping points analysis (Tables 2 & 3). The percentage of time spent fixating on green elements while walking was negatively associated with changes in STAI and positively with perceived restorativeness, while the percentage of time spent fixating on grey elements demonstrated inverse trends (Table 3). Thus, more fixation on green elements reduced state anxiety and increased perceived restorativeness, while fixation on grey elements showed opposite trends. Nature-relatedness was positively associated with perceived restorativeness, and childhood residency negatively correlated with perceived restorativeness in the grey group (Table 3). No significant relationships were found between the percentage of time spent fixating on green or grey elements and changes in PANAS (positive and negative) or NCPCT scores (Tables S11-S16). Base models for the STAI and PRS models can be found in supplementary material (Tables. S17-S20).

Wellbeing outcomes were also related to the percentage of time fixating on specific natural elements (Table 4). Changes in STAI (state) scores before and after the walk were negatively correlated with the percentage of time fixating at trees, indicating that participants who spent more time gazing at trees reported a greater reduction in state anxiety. The perceived restorativeness models indicated that, along with trees, both bushes and lawns were marginally ($p<0.1$) and positively related to increased perceived restorativeness (Table 4). Participants who spent more time gazing at trees, bushes, or lawns during their walk reported significantly higher perceived restorativeness than those who spent less time looking at these elements. Age and cloud cover were significantly related to decreases in state anxiety from the beginning to the end of the walk. Other control variables were either removed from the model based on AIC selection or found to be insignificant (Table 4). Nature-relatedness was positively correlated with perceived restorativeness. No significant relationships were observed between PANAS (positive and negative) or NCPCT scores and the fixation on any natural elements while walking (Tables S21-

S23). Base models for the STAI and PRS models can be found in the supplementary material (Tables. S24-S25).

---------[Tables 3,4 about here]----------

Discussion

Empirical studies show that nature interactions can mitigate urban living's negative effects on health and wellbeing (Hartig & Kahn, 2016; Jackson, 2003; Kabisch et al., 2017). Enhancing urban design for the wellbeing of residents and nature requires a deeper understanding of how specific natural or green elements can provide benefits to humans (Colléony and Shwartz, 2019). Our study used mobile eye tracking in outdoor settings to examine the relationships between human wellbeing and visual attention to green and grey elements. This is, to our knowledge, one of the first attempts to explore these relationships while participants actively moved through a complex urban landscape, thereby aiming to bridge existing knowledge gaps in this area. We demonstrated that, despite some technological challenges and limitations, eye tracking can be a valuable tool to explore the relationship between visual attention to natural elements and wellbeing in real-life, outdoor environments. Overall, our findings supported the relationship between anxiety and restorativeness measures and the viewing of green or grey elements. Among participants who undertook the same walk, those who focused more on green elements experienced enhanced wellbeing benefits compared to those who primarily viewed man-made built elements. Our results aligned with the findings of previous stationary indoor studies that directing visual attention toward nature instead of the built environment can reduce anxiety and increase perceived restorativeness (i.e., Liu et al., 2022; Nordh et al., 2013).

To date, most studies that have explored the relationship between green or nature and wellbeing remain correlative and address nature as a 'black box' (Pett et al., 2016; Shanahan et al., 2015). Our results showed that the time spent looking at trees specifically was associated with a reduction in state anxiety and increased perceived restorativeness. Increased perceived restorativeness was also related to the percentage of time spent viewing bushes and lawn, but viewing trees was the strongest predictor. This could be due to individuals associating trees with additional benefits compared to other green elements. For example, previous studies have found that the thermal comfort benefits of trees are significantly related to psychological parameters (Elsadek et al., 2019; Ren et al., 2022). These results strengthen the value of planting trees in cities to provide various ecosystem services to residents (Endreny, 2018; Gómez et al., 2001).

Regarding positive and negative affect, our results align with studies suggesting that walking in natural settings offers specific affective benefits such as reduced rumination or decreased negative affect rather than increased positive affect (Bratman, Hamilton, et al., 2015). Positive and negative affect are distinct (Diener & Emmons, 1984), with differing impacts observed in green versus urban settings (Legrand et al., 2022). However, our findings were somewhat inconsistent. In the first analysis, participants who were primed to focus on green elements and stopped in areas dominated by nature showed an increase in positive affect and a decrease in negative affect. Similarly, those in the mixed element group experienced a decrease in negative affect after the walk, but no differences were observed for participants primed towards, and stopping at points dominated by man-made elements. In contrast, the second and third analysis showed that visual attention towards green or grey elements did not demonstrate any effect on affect. Inconsistencies in our findings could be attributed to variations in analytical approaches. First, the differences observed in the green and mixed groups could have been obscured when the analysis encompassed the entire study population. Furthermore, the second and third analysis, focusing on differences in affect, did not account for among individual variation, potentially concealing the effects by not considering the mean responses. Alternatively, what the participants looked at rather than for how long could also explain our findings. Wellbeing from nature depends not solely on the total time people spend in nature, but rather about the level of engagement (Richardson et al. 2021). Our study did not measure momentary/in situ positive or negative affect, limiting our ability to relate specific interactions with wellbeing outcomes. Future research can benefit from investigating how affect or emotions are related to the length of time looking at specific elements of nature.

Regarding cognitive measures, while prior studies linked gaze behavior with reduced cognitive effort for attention recovery (Cottet et al., 2018; Franěk et al., 2018), our study recorded no significant differences between experimental groups or in response to visual attention to specific green, grey, and specific natural elements. In our experiment, all participants walked on the same route in an urban environment (unlike other studies that mostly compare urban to natural walks (e.g., Bielinis et al., 2018; Bratman, Daily, et al., 2015; Takayama et al., 2014). The urban environment is complex and dynamic, and other factors beyond visual attention can contribute to (increase or decrease) the ability to restore attention and provide cognitive benefits. Natural sounds, for instance, are known to enhance attention restoration (Van Hedger et al., 2019), yet our route exposed participants to urban noises like traffic and construction. Studies have shown that cognitive performance improvements are related to natural environments, while urban environments had the opposite effect (Stenfors et al., 2019). Therefore, our urban route might not have led to observable changes in cognitive performance. The only marginally significant difference in the before / after scores for attention performance was observed in the mixed group, where participants were not specifically instructed to direct their attention towards any particular construct. It is plausible that the participants in the green and grey groups expended significant effort to adhere to their tasks, aware that their eye movements were under observation. This heightened effort might have impeded their ability to derive cognitive benefits from the walk.

Considering these factors, we believe that further research using eye tracking technology in outdoor environments would help strengthen our understanding of the relationship between cognitive benefits and elements of nature.

The results of this study may be explained by common heuristics. Daniel Kahneman popularized the term 'what you see is all there is' in his description of the process by which the brain is susceptible to cognitive biases that the information an individual has is all of the relevant information (Kahneman, 2011). This phenomenon is usually viewed negatively, especially when it comes to decision making (Kahneman et al., 2011), but if this mechanism underlies the association between visual attention and mental benefits from nature, individuals could use this bias to their advantage. Heuristics are theorized to have developed to ease decision making (Haselton et al., 2015), and other studies have identified situations where heuristics can be advantageous to individuals (Gigerenzer, 2008). Uncovering simple behavior changes that individuals can implement in their daily lives to improve their mental health, especially in areas of higher mental burden (Gruebner et al., 2017), can lead to greater human wellbeing outcomes. For example, urban dwellers are already at a greater risk of mental illness, including 20% more anxiety compared to rural dwellers (Bhugra et al., 2019). Policies can be implemented to encourage urban dwellers to be more mindful of elements of nature in their daily routine, reducing anxiety and increasing restorativeness.

Understanding the effects of natural elements on mental state can also inform practitioners, such as landscape architecture and urban designers. We suggest specifically 1) the creation of spaces that have natural elements for individuals to look at; 2) designing natural spaces that encourage people to look at and interact with nature; and 3) including a greater amount of specific green elements such as trees, bushes, and lawns. If planners and landscape architects can attract people's attention to nature in their daily lives, such as on the way to work or school, this could potentially significantly reduce an individual's daily mental burden. We suggest that future studies use eye tracking while considering landscapes with higher prevalence of these elements. Another benefit, beyond mental health, of increasing the ability of individuals to experience psychological restoration from natural elements is that those who benefit psychologically from nature may also be more likely to protect it (Hartig et al., 2007).

Limitations and future directions

Our study, while offering valuable insights into the relationship between visual attention to natural elements and wellbeing, also confronts several limitations. Due to the need to avoid bright sunlight (i.e., restricted working hours), the experiment spanned nine months. This extended duration, coupled with its outdoor field nature, posed challenges in accounting for environmental factors such as sound, noise, and smell, which may vary throughout the year. These factors are important as evidence suggests that other sensory elements can contribute significantly to wellbeing (Franco et al., 2017). We did not monitor sensory elements beyond visual attention that could have affected individual wellbeing, such as sounds or smells. As our environmental control variables were not significantly different between the participant groups, we do not suspect that sounds and smells would have been significantly different between the groups. The random distribution of participants in the conditions further minimizes potential biases that could influence our results. However, future studies could benefit from shorter data collection periods, monitoring these confounding factors, and exploring ways to mitigate them, such as using headphones to shield noise. Care must be taken to ensure that such measures do not compromise the authenticity of the nature experience or introduce additional bias. Future research should also seek to understand to what extent visual versus other sensory interactions with nature contribute to human wellbeing (Colléony et al. 2021).

Furthermore, the walk's duration varied slightly among participants, and we encountered technical issues with the Tobii Pro 2 Glasses, which performed suboptimally in bright light, humid or warm conditions (above 28 degrees C) and following sudden or fast head movements. To mitigate these challenges, we adjusted participants' start times around the weather, provided them with baseball caps, and instructed them to look straight through the lens while minimizing fast movements. Despite these measures, the number of recorded fixations still varied between participants. We addressed this by analyzing only the percentages of fixation time. These efforts, combined with the random assignment of participants to conditions, likely minimized biases from these issues and other disturbances during the walk (e.g., human activity). Notably, these challenges predominantly affected the moving part of the analysis. The fact that both eye-tracking analyses yielded similar results strengthened our confidence in their robustness. Nonetheless, we cannot completely dismiss these potential flaws, and future research should consider them in experimental design, striving to standardize tracking time and conditions as much as possible. Finally, our exclusive focus on fixations as the eye-tracking metric is a limitation. Future studies would benefit from including a wider range of eye tracking metrics, such as saccades and pupil dilation, to gain a more comprehensive view of visual engagement and cognitive processing in natural settings, thus enhancing the robustness and validity of outdoor environmental research findings.

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Conclusions

Urbanization's impact on health and wellbeing, characterized by stress and mental fatigue, is increasingly recognized, with nature seen as a potential remedy (Bertram & Rehdanz, 2015; Lederbogen et al., 2011). However, the specific natural elements that most effectively enhance wellbeing in urban environments are yet to be fully understood. This understanding is crucial for aligning public health and nature conservation goals, fostering connections to nature, and designing sustainable cities (Colléony and Shwartz 2019). Our study contributes to bridging this knowledge gap, demonstrating that simply directing visual to green elements like trees, rather than grey, significantly reduces anxiety and boosts restorativeness during routine urban walks. Participants who focused more on greenery experienced these benefits, while those observing grey elements did not. This finding implies that a subtle shift in attention towards nature can substantially improve daily wellbeing in urban areas. Such insights are vital for urban planning, suggesting the creation of spaces that offer not just access to natural elements, but also promote engagement with nature, potentially influencing wellbeing and pro-conservation behaviors (Mackay & Schmitt, 2019; Shwartz et al., 2023). Understanding which natural elements confer these benefits is key to transforming cities into healthier habitats for humans and wildlife alike. Our research highlights the importance of further exploring both visual and other sensory interactions with nature in urban contexts, underscoring their significance in enhancing mental health and wellbeing. We also demonstrate for the first time the potential benefits of using mobile eye tracking technology in outdoor urban environments to explore how visual intake of nature elements influences wellbeing, though challenges persist to effectively utilize this technology outdoors.

Ethics Statement

Permission for this study was granted by the Technion Social and Behavioral Sciences Institutional Review Board. Participants were paid approximately $15 (50 ₪) to participate in the study and signed informed consent.

Contributions of Authors

Whitney Fleming conducted statistical analyses, and drafted and edited the manuscript and its supplemental material. Brian Rizowy conducted the field experiments and provided technical analysis of eye tracking data. Assaf Shwartz contributed to all aspects of this manuscript.

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Figures and Tables:

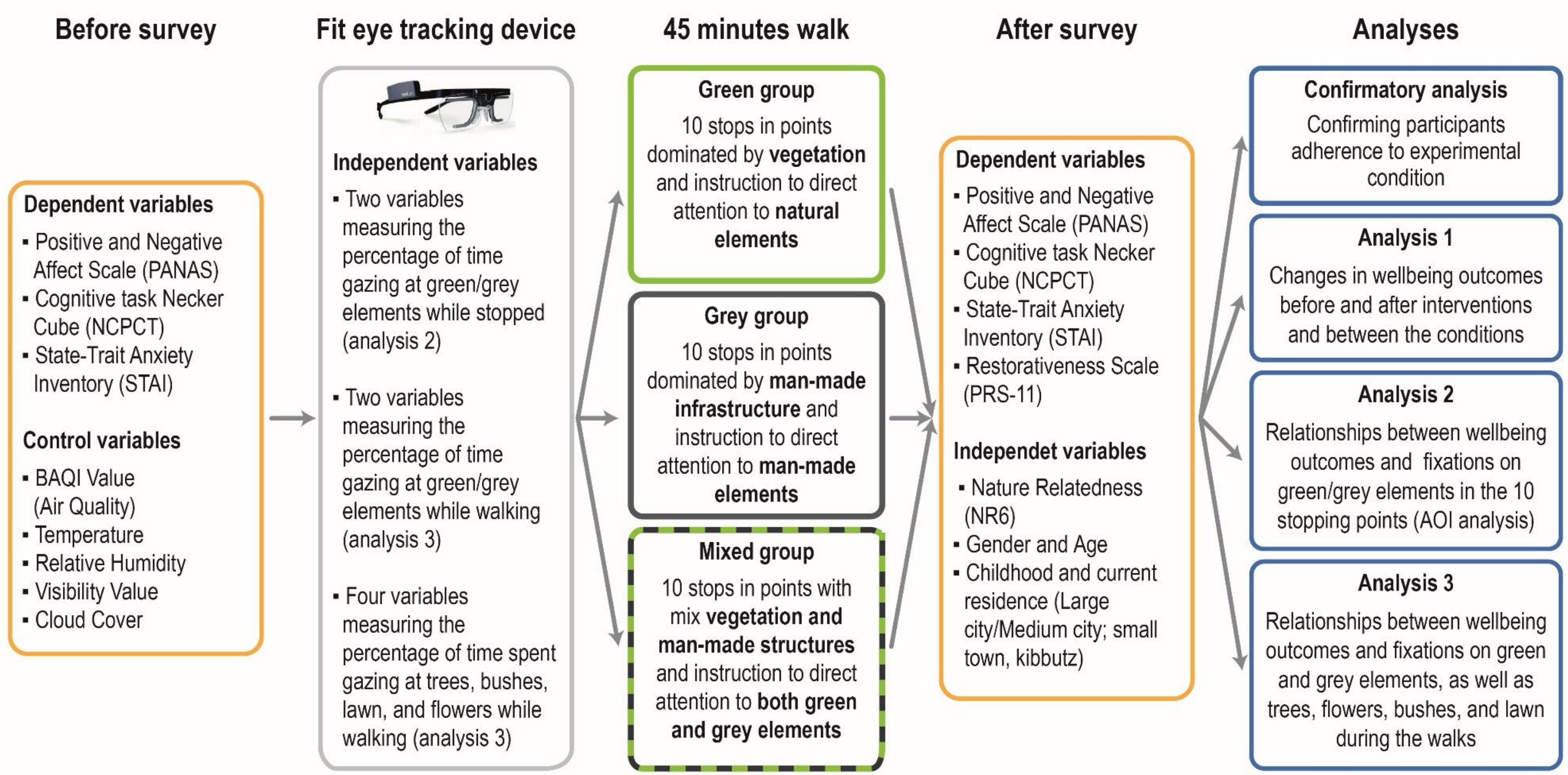

Figure 1 – Research framework flow chart providing an overview of the experimental design, the variables measured, and the analyses conducted in this study.

Source: Esri, Maxar, Earthstar Geographics, and the GIS User Community

Figure 2 – Map illustrating the study area in and around the Technion campus in Haifa, the walking route and the designated stopping points. Participants, based on their group allocation, stopped at 10 specific points. These points are marked as green, grey, and mixed color, representing points predominantly featuring vegetation, man-made structures, or a blend of both, respectively. Figure S1 in Supporting Information provides the images and heat maps of the 30 points.

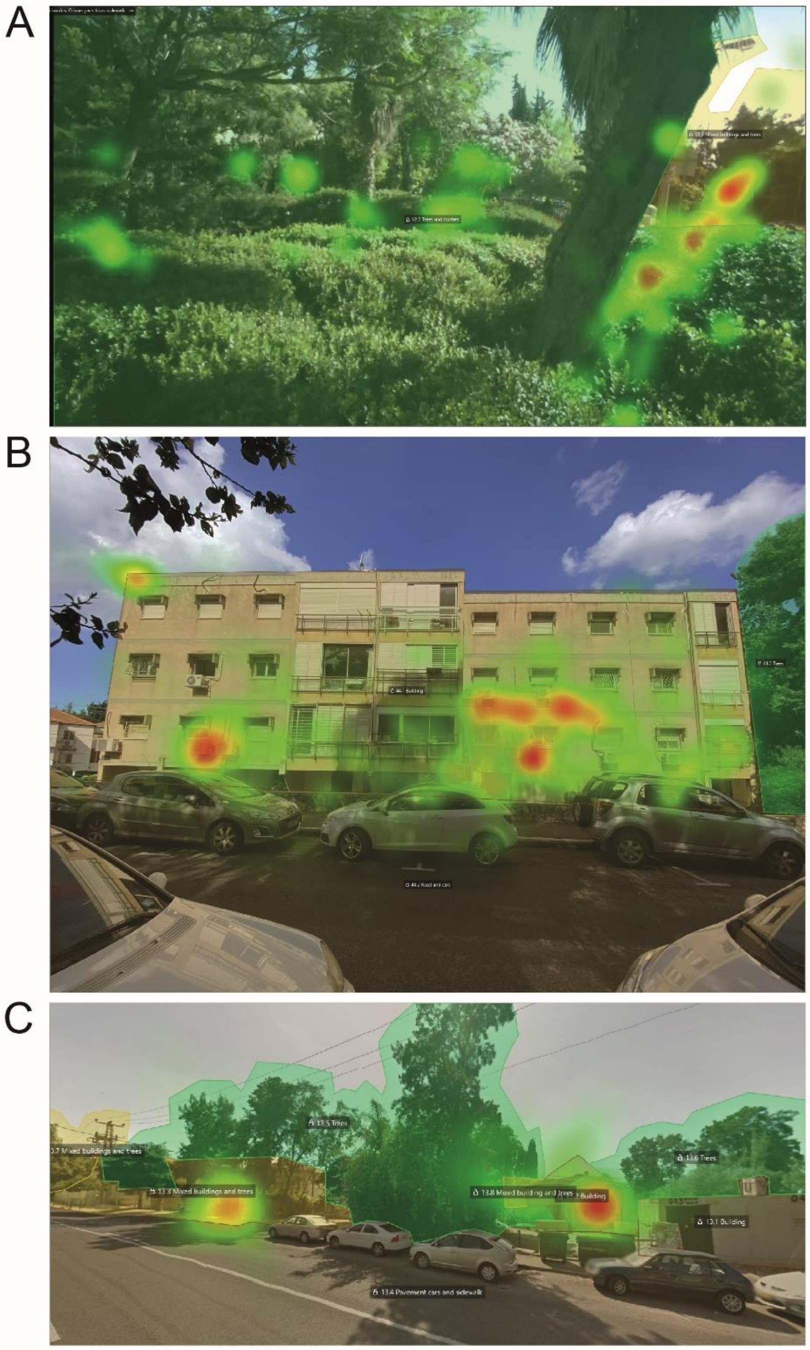

Figure 3. Examples of stopping points for the green (a), grey (b) and mixed (c) groups in the experiment. Heatmaps of participant’s eye movements are overlayed on photos from the eye-tracking glasses with polygons classifying the main features used in this analysis. For a complete view of all stopping points, their categorization into the three conditions, and representative heatmaps see Fig. S1.

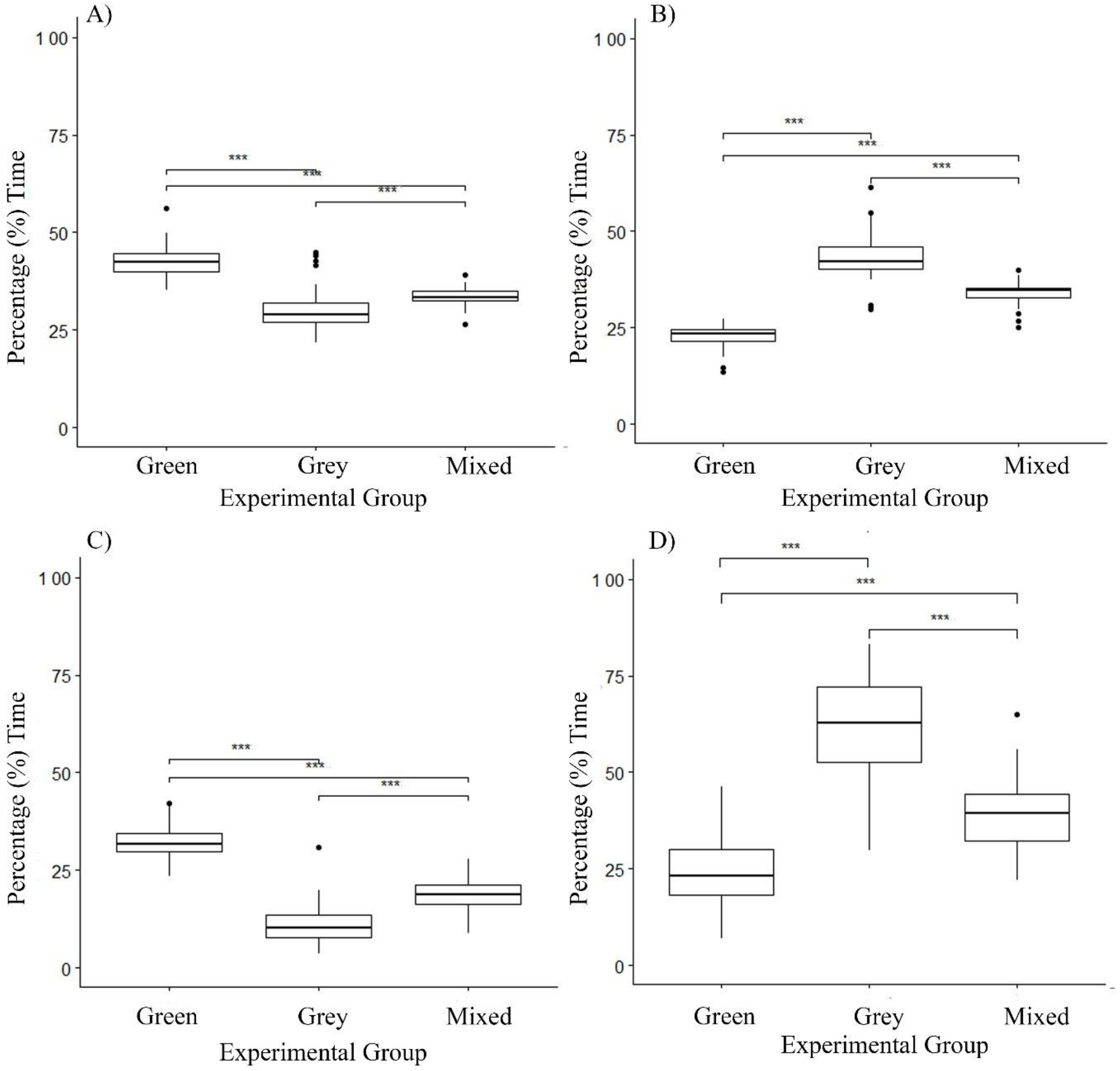

Figure 4. Boxplots presenting the differences in the percentage of total fixation time recorded for participants in each experimental condition (Green, Grey, or Mixed) for (A) green elements while stopped; (B) grey elements while stopped; (C) green elements while walking; and (D) grey elements while walking. Significant differences are indicated from Kruskal-Wallis tests (***=p<.001).

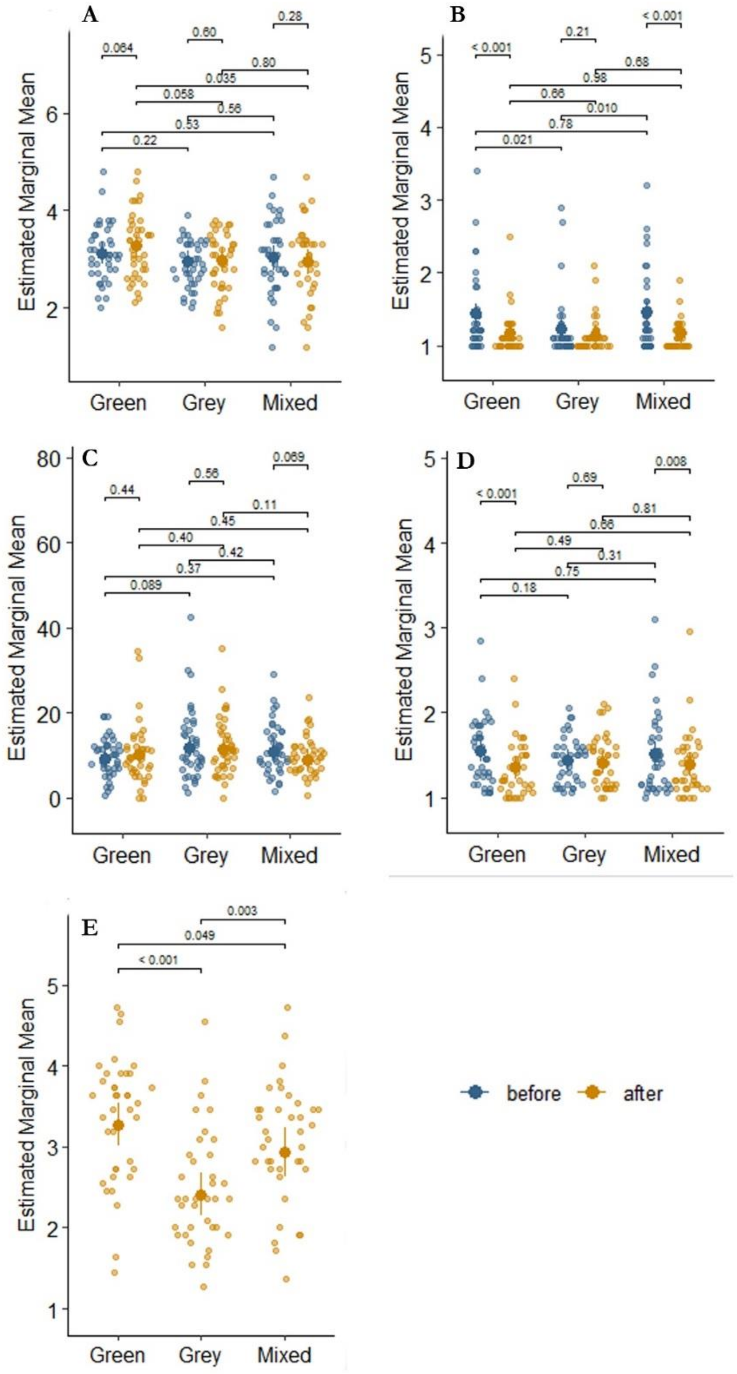

Figure 5. Estimated marginal means of differences between groups (green, grey, and mixed) before and after a walk with p-values for: A) changes in Positive affect (PA); B) changes in Negative affect (NA); C) changes in NCPCT; D) changes in STAI State scores; E) perceived restorativeness (only measured after walk).

Table 1. Results of mixed models for repeated measures (MMRM) for positive affect (PA), negative affect (NA), NCPCT, and STAI state. As well as results of a linear model for perceived restorativeness (PRS). The table includes estimated coefficients for modeled independent variables with ± standard error of the estimated coefficients. Significance levels are shown: *p < 0.05, **p < 0.01, ***p < 0.001.

	Between Groups				
Independent Variables	**PA**	**NA**	**NCPCT**	**STAI State**	**PRS**
	Coefficient ± St. Error	Coefficient ± St. Error	Coefficient ± St. Error	Coefficient ± St. Error	Coefficient ± St. Error
Condition (Grey)	-0.18 ± 0.15	-0.21 ± 0.09	2.56 ± 1.50	-0.11 ± 0.09	-0.86 ± 0.17***
Condition (Mixed)	-0.10 ± 0.15	0.03 ± 0.09	1.35 ± 1.52	-0.03 ± 0.09	-0.34 ± 0.17*
Time (After)	0.15 ± 0.08	-0.25 ± 0.07***	0.74 ± 0.96	-0.19 ± 0.05***	-
Gender	-0.04 ± 0.12	-0.08 ± 0.07	0.45 ± 1.10	-0.10 ± 0.07	0.13 ± 0.14
Childhood Residence (Large city/Medium city)	-0.18 ± 0.16	-0.04 ± 0.09	-3.55 ± 1.50*	0.03 ± 0.09	0.021 ± 0.19
Childhood Residence (Small city)	-0.20 ± 0.15	0.14 ± 0.08	-1.41 ± 1.40	0.07 ± 0.08	0.26 ± 0.18
Current Residence (Large city/Medium city)	0.00 ± 0.23	-0.10 ± 0.13	2.59 ± 2.15	-0.01 ± 0.13	0.27 ± 0.28
Current Residence (Small city)	0.05 ± 0.24	-0.07 ± 0.13	0.87 ± 2.23	0.05 ± 0.13	0.07 ± 0.29
Nature Relatedness (NR6)	0.20 ± 0.07**	-0.03 ± 0.04	0.67 ± 0.67	-0.07 ± 0.04	0.30 ± 0.08***
Age	0.01 ± 0.01	0.01 ± 0.01	0.07 ± 0.10	0.01 ± 0.01	-0.01 ± 0.01
BAQI Value	-0.01 ± 0.01	0.00 ± 0.00	-0.01 ± 0.08	0.00 ± 0.00	0.01 ± 0.01
Temperature	-0.01 ± 0.01	-0.01 ± 0.01	-0.19 ± 0.11	0.00 ± 0.01	0.00 ± 0.01
Relative Humidity	0.00 ± 0.00	0.00 ± 0.00	-0.01 ± 0.04	0.00 ± 0.00	-0.00 ± 0.01
Visibility Value	0.00 ± 0.01	0.00 ± 0.00	-0.06 ± 0.07	0.00 ± 0.00	0.012 ± 0.01
Cloud Cover	0.00 ± 0.00	0.00 ± 0.00	0.01 ± 0.02	0.00 ± 0.00	0.02 ± 0.00
Condition Grey *Time	-0.11 ± 0.11	0.17 ± 0.09	-1.31 ± 1.36	0.17 ± 0.06**	-
Condition Mixed *Time	-0.23 ± 0.11*	-0.03 ± 0.09	-2.59 ± 1.36	0.07 ± 0.07	-

Table 2. Results of linear models exploring the relationships between differences in STAI state (before/after) and perceived restorativeness (PRS) and the percentage of time fixating at green or

grey elements while stopped at AOIs. The table includes estimated coefficients for modeled independent variables after AIC model selection and model fit statistics, with ± standard error of the estimated coefficients. Significance levels are shown: *p < 0.05, **p < 0.01, ***p < 0.001.

Linear Models for AOIs				
Independent Variables	**STAI Green** Coefficient ± St. Error	**STAI Grey** Coefficient ± St. Error	**PRS Green** Coefficient ± St. Error	**PRS Grey** Coefficient ± St. Error
Percentage time viewing	-0.96 ± 0.38*	0.78 ± 0.27**	2.93 ± 1.10**	-3.21 ± 0.74***
Age	-0.01 ± 0.00*	-0.01 ± 0.00**	-	-
Cloud Cover	-0.00 ± 0.00*	-0.00 ± 0.00*	-	-
Nature Relatedness	-	-0.05 ± 0.03	0.30 ± 0.09**	0.33 ± 0.08***
Temperature	-	0.01 ± 0.01	-	-
Final AIC	24.051	21.722	242.576	232.109
Adjusted R^2	0.132	0.166	0.151	0.232

Table 3. Results of linear models of percentage time gazing at green or grey elements while walking on changes in STAI state and perceived restorativeness (PRS). The table includes estimated coefficients for modeled independent variables after AIC model selection and model fit

statistics, with ± standard error of the estimated coefficients. Significance levels are shown: *p < 0.05, **p < 0.01, ***p < 0.001.

Linear Models While Walking: Green and Grey Overall

Independent Variables	**STAI Green** Coefficient ± St. Error	**STAI Grey** Coefficient ± St. Error	**PRS Green** Coefficient ± St. Error	**PRS Grey** Coefficient ± St. Error
Percentage time viewing	-0.62 ± 0.26*****	0.44 ± 0.14******	3.54 ± 0.70*******	-2.13 ± 0.37 *******
Age	-0.01 ± 0.00*****	-0.01 ± 0.00	-	-
Child residency (large or medium city)	-	-	-	0.07 ± 0.17
Child residency (small city)	-	-	-	0.35 ± 0.17*****
Cloud Cover	-0.00 ± 0.00	-0.00 ± 0.00*****	-	
Nature Relatedness	-0.04 ± 0.03	-	0.30 ± 0.08*******	0.29 ± 0.08*******
Temperature	-	0.01 ± 0.01	-	-
Visibility Value	-	-	-	0.01 ± 0.01
Final AIC	24.267	21.027	226.484	222.639
Adjusted R²	0.138	0.164	0.273	0.318

Table 4. Results of linear models of percentage time gazing at specific natural elements (trees, bushes, lawn, and flowers) while walking on perceived restorativeness (PRS) and STAI scores. The table includes estimated coefficients for modeled independent variables after AIC model selection, and model fit statistics, with ± standard error of the estimated coefficients. Significance levels are shown: ǂp<0.1 *p < 0.05, **p < 0.01, ***p < 0.001.

Linear Models While Walking: Specific Green Elements

	STAI	PRS
Independent Variables	Coefficient ± St. Error	Coefficient ± St. Error
Percentage time viewing trees	-1.54 ± 0.57**	5.88 ± 1.58***
Percentage time viewing bushes	-	2.22 ± 1.18ǂ
Percentage time viewing lawn	-	10.29 ± 5.36ǂ
Percentage time viewing flowers	-	-
Age	-0.01 ± 0.00	-
Cloud Cover	-0.00 ± 0.00*	-
Nature Relatedness	-	0.25 ± 0.09**
Temperature	0.01 ± 0.01	-
Final AIC	23.590	226.098
Adjusted R^2	0.143	0.289