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The potential of applying immersive virtual environment to biophilic building design: A pilot study

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ABSTRACT

Biophilic design is a popular form of sustainable building design because of its potential to contribute to human health and wellbeing. While many design processes are now mediated by computer technologies such as immersive virtual environments (IVEs), the reliability of IVEs to create the same benefits of biophilic designs as *in-situ* is yet to be determined. To this end, we conducted a comparative study to measure participants' mood, cognitive performance, and stress level in *in-situ* and IVE experiment settings. A within-subject experimental design with thirty-five college students was applied to both *in-situ* and IVE experiments. The positive and negative scale (PANAS), visual working memory performance, and the sympathetic nervous system index and parasympathetic nervous system index were used as measures for mood, cognitive performance, and stress level of a participant, respectively. We found that natural element exposure in IVEs reduced negative mood in the same way as natural element exposure *in-situ*. However, we did not find the same for positive affect, visual working memory, and stress level tests. Factors such as the experimental procedure, exposure time to nature in both *in-situ* and IVE settings, and characteristics of participants may contribute to the results. Future research is needed to further investigate the impact of such factors and develop reliable experimental protocols.

1. Introduction

In 1964, Dr. Erich Fromm, a German-born American social psychologist, used the term biophilia for the first time in his book to describe "the passionate love of life and of all that is alive" [1]. The term biophilia has a root in Greek works bio ("life") and philia ("affinity") [2], which means "love of life or living systems" [3], highlighting the psychological orientation of being engaged to all species [3]. An American biologist, Edward O. Wilson used this term later, and describe it as "the urge to affiliate with other forms of life" [1]. Wilson argued that biophilia had roots in our humanity and that it created a connection between humans and all other creatures [4]. Later, Wilson and his colleague, Stephen R. Kellert, introduced the biophilia hypothesis as part of the theories of evolutionary psychology [5]. Kellert also introduced biophilic design as a concept depicting the incorporation of natural features and systems into an indoor environment to create more sustainable interior environments [6].

As Kellert described, humans are a bicultural creature, which means humans can learn certain behaviors over time [7]. There are many cases that show a human tendency to nature such as the gardens of Babylon and the leafy filigrees of Rococo design [8]. Although in modern times humans are facing the challenge of losing interactions with nature due to urbanization [9], they can make a connection to the natural world through biophilic design, such as bringing natural components or representations of nature into the built environment to satisfy the propensity of humans toward nature [6]. As an architectural design approach, biophilic design is a thoughtful attempt to understand humans' inherent affinity to affiliate with nature [4]. Designers have applied biophilic design at both small (building) [10] and large (urban designing) scales [11]. It is considered to have physical and psychological benefits for building occupants and city residents [12,13].

On the other hand, using natural elements in building design isn't always beneficial [14]. The natural world is overflowing with dangers that may lead to fears or "biophobic" reactions, for example fears of animals and nature [15]. Natural environments may also evoke anxiety [16]. Some examples of environmental anxieties are enclosed spaces [15], height [15], and gloomy spaces [17]. Similarly, while some studies have found that exposure to nature improves cognitive performance [18,19], other studies have not found improvements in cognitive performance after exposure to nature [20,21]. Therefore, design plays an

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important role in determining the effectiveness of biophilic features.

It is also recognized that the benefits of biophilic designs are not delivered automatically without careful planning and design [22]. Especially, building design processes are now commonly mediated by computing and information technologies such as computer aided design (CAD) [23], building information modeling (BIM) [24], and virtual reality (VR) [25]), which significantly influence decisions made during design [26]. It is thus important to know how technologies may have an impact on human's perception of biophilic design features.

Recently, the emerging applications of immersive virtual environments (IVEs) in building designs have been increasingly reported. For example, studies show that IVEs may enhance project satisfaction in the long run and save money [27], and support evidence-based design (EBD) [28]. Empirical studies have also shown the potential of such applications in eliciting human responses to building design features [23]. However, the impact of IVEs on biophilic design is not fully understood due to the unknown impact of the technology on human users.

Since the benefits of biophilic designs are often reflected in the improvement of mood, cognitive performance, and stress level of participants [8], we are interested in understanding the potential of replicating such benefits in IVEs comparable to *in-situ* conditions. In other words, the use of IVEs to support biophilic design should not interfere with or alter observations of the three measures compared to *in-situ* environments. To this purpose, this study is designed to explore four questions:

- Does natural element exposure in IVE reduce the negative mood of participants in the same way as natural element exposure *in-situ*?
- Does natural element exposure in IVE increase the positive mood of participants in the same way as natural element exposure *in-situ*?
- Does natural element exposure have the same impact on the cognitive performance of participants in both IVE and *in-situ*?
- Does natural element exposure in IVE reduce the stress level of participants in the same way as natural element exposure *in-situ*?

In the following, we will discuss existing literature related to the topic, the design of research focusing on the four questions, data analysis, and conclusions and future studies.

2. Literature review

2.1. Humans and biophilic design

The relationship between humans and biophilic design can be understood from three perspectives: the evolutionary perspective [29], evidence of the impact of nature on humans [8], and a typology of values of nature [30].

- Evolutionary perspective: the evolutionary perspective [29] suggests that forces of evolution have shaped modern humans. The concept of the Environment of Evolutionary Adaptation (EEA) was introduced by John Bowlby [29] to describe the environment to which a species was adapted, as well as conditions in which humans spent over 99% of their evolutionary history [29,31,32]. Due to urbanization, the environment that humans now experience is different from the EEA. Urban living is a new phenomenon that most of the world's population now faces [33]. According to Sharp [34], "Urbanization will continue to accelerate in the coming decades". Six out of every ten people will live in cities by 2030 and this number will rise to seven out of ten people by 2050 [35]. Although urbanization has advantages such as the ease of access to essential amenities, it reduces our connection to nature, which is an integral component of the EEA. As a solution, the presence of biophilic elements is essential to human mental health and wellbeing [36].
- Nature's effect on humans: Studies have provided evidence that exposures to nature have a positive impact on humans mentally [37], physically [38,39], and economically [40]. For example, many studis have supported that people who live in urban green spaces have significantly better mental health [41] and health-related behaviors [42]; while living in crowded cities increases stress-related disorders [43]. Studies show that spending time in nature can have a positive impact on human immune function [13] and mood states and stress [44], increase the level of physical activities that has positive effects on psychological health [39], decreases the risk of coronary heart disease and stroke [38], improve the healing process of patients [45], increase productivity at workplaces [46], and improve cognitive performance [18]. These beneficial impacts can happen through active [47] or passive [48] involvement with nature. Possible reasons include:
  1) Being in nature is associated with physical activities, which boosts health [49];
  2) Activities in nature potentially lead to more social interactions, which has the potential to improve health [49];
  3) Nature helps free humans from everyday routines [49]; and
  4) Nature may redcue stress and its negative impact one's psychological and physical health [50].

Based on such general understanding, Stephen Kellert established a framework, known as the Attributes of Biophilic Design, to satisfy an experience with nature in the built environment [51]. These characteristics are guidelines that architects and designers can apply to their designs to promote people's physical and mental health. Kellert categorized these attributes into three main groups:

1. The first group is called "*direct experience of nature*" or "*nature-in-the-space patterns*". These attributes indicate a state of direct connection with nature elements in the built environment, such as light, air, water, plants, and so on [8,12].
2. The second group, which is known as "*indirect experience of nature*" or "*natural analogues patterns*", indicates a connection with elements that represent nature in the built environment [8,12], for example a picture of nature, use of materials and color representing nature, and simulation of natural lighting.
3. The third group, known as "*experience of space and place*" or "*nature-of-the-space patterns*", are spatial features that remind humans of the complexity and order that they see in nature [8,12].

2.2. Measuring the benefits of biophilic design to humans

The benefits of biophilic design to humans can be determined by measuring stress reduction, cognitive function, and self-reported emotional changes. For example, many studies show that people who experience environments that have natural elements, like trees, tend to feel safer and more comfortable [52,53] and show improvements in mental health and tranquility [54]; other studies show better physiological responses when people are exposed to a natural environment [13,55,56]. Those studies reveal that stress reduction [39,57] is essential to generating such benefits.

Environmental conditions can induce physiological stress in humans [58]. The human body relies on the autonomic nervous system (ANS) and its subsystems (i.e., the sympathetic nervous system (SNS) and the parasympathetic nervous system (PNS)) to handle stress [59]. The sympathetic nervous system (SNS) is active in response to body emergencies (e.g., Fight or Flight). On the other hand, the parasympathetic nervous system (PNS) balances the body homeostasis by releasing acetylcholine (ACH) via the vagus nerve [60]. Heart rate variability (HRV) is regarded as an effective measure for observing the SNS and the PNS [61–63]. There are two different types of metrics for measuring HRV, time-domain measures and frequency-domain measures [64]. The time-domain metrics include the R-wave to R-wave interval (R-R interval), the standard deviation of the NN intervals (i.e., the normal-to-normal (NN) interval, another way to refer to the R-R interval) (SDNN), and the square root of the mean of the sum of the squares of differences between successive NN intervals (RMSSD). The conventional frequency-domain metrics include the low frequency band (LF), the high-frequency band (LH), and the low-to-high frequency ratio (LF/HF). In addition, there are HRV non-linear measures such as SD1, SD2, and SD1/SD2. SD1 is the "Poincaré plot standard deviation along the line of identity"; while SD1 is "Poincaré plot standard deviation perpendicular the line of identity" [65]. These metrics can be used for analyzing HRV, and stress in humans.

In addition, studies show that the restorative effect of nature is associated with better cognitive function [47,66]. Cognitive function can be measured by performance on visual working memory tasks [67,68]. For example, studies have tested participants' visual working memory for colored shapes. Arrays of multiple colored shapes are presented for a brief time (approximately 500–1000 ms) and then memory for either a color (Fig. 1), a shape (Fig. 2) or both is tested after a brief delay (approximately 1000 ms) [67,68].

Finally, researchers have often used the positive and negative affect scale (PANAS) to measure emotional changes [44,47]. The PANAS has 10 items that measure positive affect and another set of 10 items that measure negative affect. A 5-point scale from 1 (not at all) to 5 (very much) is applied. Non-clinical studies that used the PANAS have confirmed its effectiveness and reliability [69].

2.3. Immersive virtual environments and biophilic design

It is commonly recognized that changes to the design of a building become more and more costly and complex as a project progresses. Hence, early design decisions are very important. Since biophilic design is a design approach often applied using computer technologies in the early stages of design, it is critical to have a better understanding about the effectiveness of computer technologies in supporting biophilic design. Over the past decades, the use of virtual and augmented reality to improve building design processes has been extensively explored [70]. Technologies like immersive virtual environments (IVEs) have shown the potential of applications to improve performance at different stages of a project's lifecycle [27].

However, while studies that directly investigate the impact of immersive virtual environments (IVEs) on biophilic design are still rare, a recent study has discussed the application of IVEs to biophilic design [55]. This study used stress level, cognitive performance, and self-reported mood to measure the impact of biophilic designs. The study reported that the biophilic environment, both virtual and *in-situ*, helped improving the mood and short-term memory of participants [55].

One of the challenges is an effective experimental or data collection protocol that researchers can use in virtual experiments. So far, although there are studies reporting virtual reality applications in biophilic design (e.g. Ref. [55,71,72]), most of them do not discuss their experimental protocol except one study [55]. Especially, the exposure time to biophilic features in experiments is important because it is directly related to the effectiveness of experiments [73]. Empirical studies on exposure to nature suggested that the exposure time varied depending on participants and anticipated outcome, and effects were observed as soon as 5–20 min of exposure to nature [8]. In studies [55,74,75], the exposure time was set to 5 or 6 min.

3. Method

3.1. Participants

Thirty-five university students in the discipline of construction management participated in the study. The following is a summary of the demographic information of the participants:

- Gender: 27 (male) and 8 (female),
- Age: 21 to 35 with the mean and the standard deviation as 23.5 and 3.2 respectively,
- Race and ethnicity: 28 (White), 4 (Middle Eastern), 1 (Hispanic or Latino), 1 (Asian), and 1 (Other), and
- VR experience: About 70% of participants familiar with virtual reality, and the other 30% not familiar.

3.2. Experimental procedure

Each participant completed the experiment on two separate days with a few days in between. In each visit, participants were randomly assigned to experience biophilic and non-biophilic environments in either an immersive virtual environment (IVE) or an *in-situ* environment. At the beginning of the experiment on each day, participants were asked to first complete the pre-experiment questionnaire, which was designed to collect data including participants' demographic information (e.g., age, gender, race, education level), their use of caffeine, cigarette and alcohol and activity level before experiments, their computer, game, and virtual reality experience and knowledge, and their eye and vision

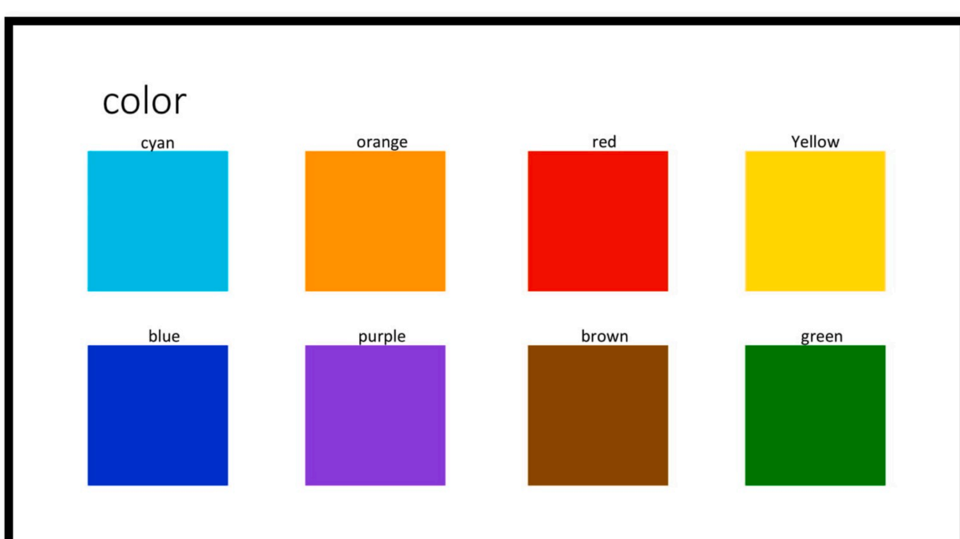

Fig. 1. Color Palette [60]

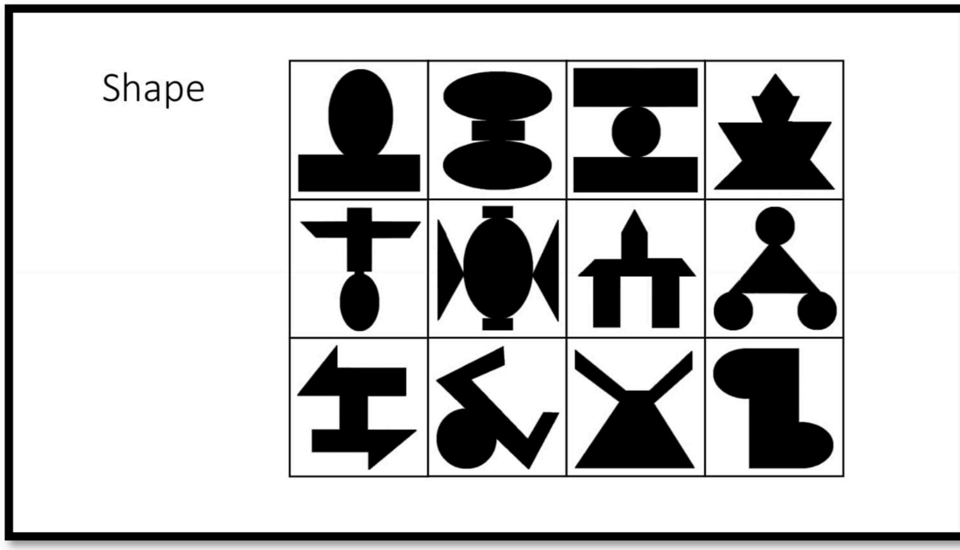

Fig. 2. Shapes [61].

conditions (See Appendix A). The following paragraphs explain the IVE and the *in-situ* experimental procedures briefly.

- *In-Situ* Experiment (Fig. 3): The experiment began with a pre-experiment questionnaire (Appendix D) followed by setting up the experiment devices. Then participants were asked at random to explore either the biophilic or the non-biophilic space for 5 min. The time period was determined based on another similar study [55]. After the experiment, participants completed a visual working memory task and a mood questionnaire, which took approximately 15 min. Then, participants changed environments and repeated the above steps. The experiment lasted approximately 1 h.
- Immersive Virtual Environment (IVE) Experiment (Fig. 4): The experiment began with device setup and a short orientation section, and then participants were asked to explore the virtual space with biophilic design or non-biophilic design for 5 min. Participants viewed the virtual environment of the study area through a Head-Mounted Device (HMD). The HMD for this study was an HTC Vive-Pro, which supports a 2880 × 1600 resolution on a dual-OLED display. After experiencing the virtual environment, participants completed a visual working memory task, which took about five to 10 min. Then participants removed the Head-Mounted Device (HMD) and filled out the mood and the presence surveys. Afterwards, the participants put on the HMD again and explored the other virtual space for 5 min. Then, the participants repeated the same steps in a different virual space. The experiment lasted about 1 h.

To reduce order effects in the experiments, we randomized the order of the *in-situ* and the IVE experiments, and the biophilic and the non-biophilic environments for each participant.

3.3. Experiment condition design

We used a sitting area with views to the outside (Fig. 5) and a lab space (Fig. 6) as the biophilic environment and the non-biophilic environment respectively for this study. The spaces are located in a building on the campus of a state university in the U.S.A. The virtual biophilic environment and the non-biophilic environment are shown in Figs. 7 and 8 respectively.

3.4. Data collection and methods

We collected the following data to answer the research questions: heart rate, positive and negative affect, visual working memory performance, and presence.

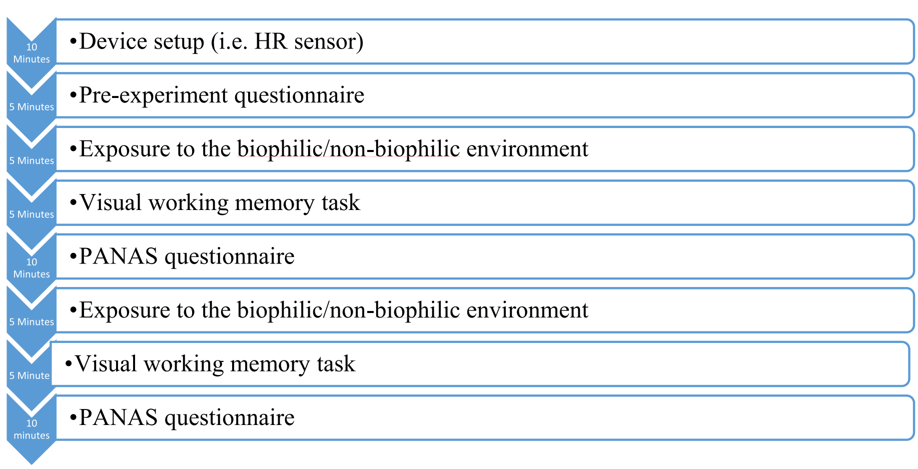

Fig. 3. Process of *in-situ* experiments.

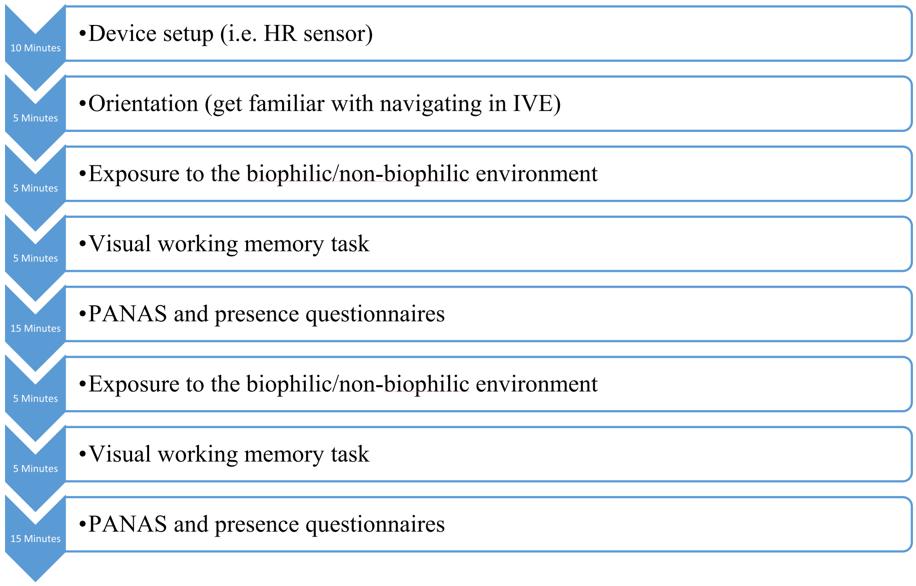

Fig. 4. Process of IVE experiments.

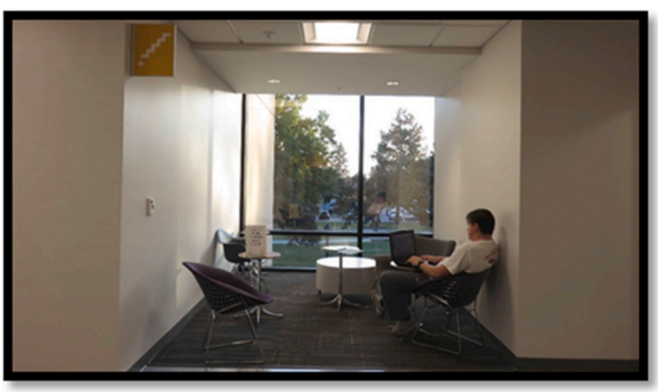

Fig. 5. Biophilic environment (*in-situ*).

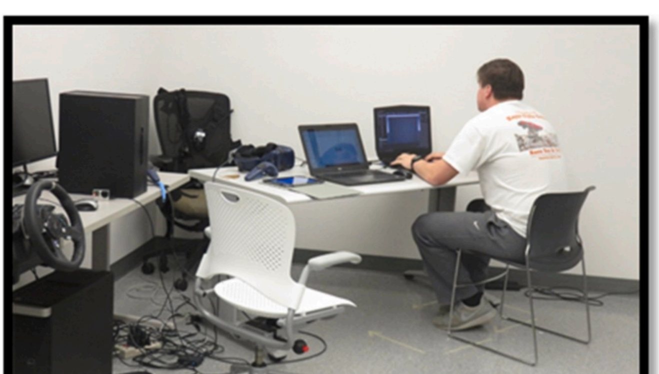

Fig. 6. Non-biophilic environment (*in-situ*).

3.4.1. Heart rate

A wireless electrode-based heart rate monitoring tool, the POLAR Ft7, was used to collect participants' heart rate (HR) data starting at the beginning of exposure to the experiment environment and ending at the completion of the visual working memory task. The participants' heart rates were monitored throughout the experiments. Data was also read and recorded using a heart rate variability logger application. We used free heart rate variability analysis software, Kubios, to analyze the collected data.

3.4.2. PANAS

The PANAS survey is attached in APPENDIX B. It took approximately 5 min for each participant to complete PANAS.

3.4.3. Presence

The basic characteristics of Immersive Virtual Environment (IVE) is creating presence [76]. The effectiveness of IVE is impacted by the degree to which participants have a sense of presence in the virtual reality environment [77,78]. Therefore, it is important to use presence as a control variable to ensure that participants are immersed properly.

We used the Igroup Presence Questionnaire (IPQ) in this study (Appendix C). The IPQ is a scale applied to measuring the sense of presence of participants in virtual environments [79]. It includes three subscales and one general item. These subscales are independent factors developed from principal component analyses, including spatial presence, involvement, and experienced realism. Presence measures the sense of being physically immersed in a virtual environment; involvement measures the degree of involvement and attention experienced by a participant in a virtual environment; and realism measures how real the virtual environment feels.

3.4.4. visual working memory

Throughout the Visual working memory test, participants answered 60 questions (20 shapes, 20 colors, and 20 shapes & colors). The order of displaying items was randomized. For each question, four items were presented and were selected from a total of eight colors (cyan, orange, red, yellow, blue, purple, brown, and green) and twelve shapes. Each question included four presentation slides. The first slide asked if the participant was ready to start; the participant pressed the space bar or said yes to see the first image. The first image included four items presented in the middle of the screen and was displayed for 500 ms, follwed by an all white image for 900 ms. Then the participant was presented with either the same image or a different image (10 questions for each question type: color, shape, and both). For the different image, one of the four items was replaced with a different item (e.g., different color, shape, or both). When the second image was presented, participants reported if the second image was the same or different from the first image. The following figures show three sets of examples in terms of color (Fig. 9), shape (Fig. 10), and their combination (Fig. 11).

Fig. 7. Biophilic environment (IVE).

Fig. 8. Non-biophilic environment (IVE).

The visual working memory tests were administered right after participants completed their biophilic or non-biophilic design exposure (Figs. 3 and 4). Simulation of test sequences was programmed to randomly draw trials for color, shape, or their combination as shown in Figs. 9–11. The sequences were displayed using a regular computer to get participants' response. In this case, the computer is the one that participants used to view designs in IVE. In the case of IVE experiments, participants were not wearing the HMD when they took the visual working memory test.

4. Analysis, results, and discussions

4.1. Positive and negative affect

4.1.1. Cronbach's alpha

Before analyzing the data related to positive and negative affect, we first examined the internal consistency of the data using Cronbach's alpha [80]. Results indicate that the internal consistency of the data is good for negative affect (i.e., 0.81, 0.84, 0.87, and 0.88, Table 1), and it is excellent for positive affect (i.e., 0.91, 0.93, and 0.94, Table 1).

4.1.2. Negative affect

To answer the question, "Does natural element exposure in IVE reduce the negative mood of participants in the same way as natural element exposure *in-situ*?", we performed two pairwise t-tests. The first t-test compared the negative affect data between biophilic and non-biophilic design *in-situ* (Table 2). The second t-test compared negative affect data between biophilic and non-biophilic design in IVEs (Table 3).

Fig. 12 is the visualization of the negative affect data for all cases, biophilic and non-biophilic cases in both IVE and *in-situ*.

The t-test on the data collected *in-situ* (Table 2) revealed a statistically significant difference between biophilic and non-biophlic designs with $p = 0.03$ (two-tailed) at a 95% confidence interval. In addition, the average negative affect (NA) score increased from biophilic ($M = 11.73$, $SD = 2.55$) to non-biophilic ($M = 12.80$, $SD = 3.93$), which suggests that biophilic design influenced, i.e., decreased, negative affect in *in-situ* conditions.

The t-test on the data collected in IVEs (Table 3) also revealed a statistically significant difference between biophilic and non-biophilic designs with $p = 0.04$ (two-tailed) at a 95% confidence interval. The average negative affect (NA) score increased from biophilic ($M = 12.00$, $SD = 2.67$) to non-biophilic ($M = 13.53$, $SD = 5.05$), which suggests that biophilic design significantly influenced, specifically decreased, negative affect in IVEs.

The outcome based on results in Table 2 matches emprical studies on biophlic designs that claim positive impact of biophili designes on paricipants' mood (e.g. Ref. [81]). The outcome shows the effectiveness of our *in-situ* experiments and their design. The outcome based on the results in Table 3 is similar to that in Table 2. Therefore, the answer to the question is postive, i.e., based on the sample, natural element exposure in IVE reduces negative moods similar to natural element exposure *in-situ*.

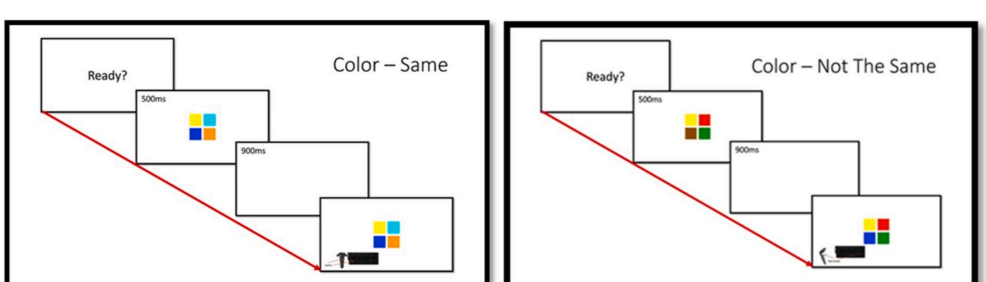

Fig. 9. Sample of the color set

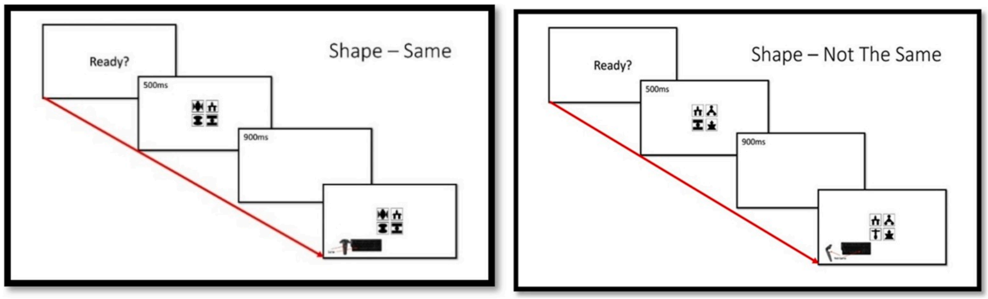

Fig. 10. Sample of the shape set.

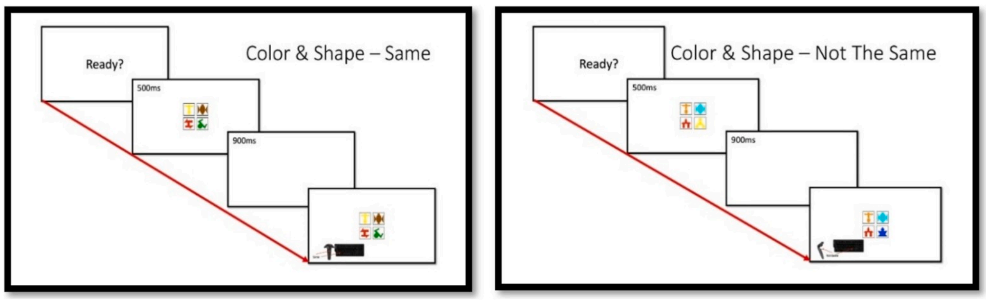

Fig. 11. Sample of the combination set.

Table 1
Cronbach's alpha results.

	A	b	C	d	e	f	g	h
# of Question	10	10	10	10	10	10	10	10
Sum of the item variances	1.68	3.27	1.67	5.17	12.55	10.44	11.31	13.35
Variance of total score	6.26	14.89	6.87	24.65	70.83	63.85	74.01	83.9
Cronbach's alpha	0.81	0.87	0.84	0.88	0.91	0.93	0.94	0.93

Notes: a. Negative affect (biophilic) in-situ; b. Negative affect (non-biophilic) in-situ; c. Negative affect (biophilic) IVE; d. Negative affect (non-biophilic) IVE; e. Positive affect (biophilic) in-situ; f. Positive affect (non-biophilic) in-situ; g. Positive affect (biophilic) IVE; and h. Positive affect (non-biophilic) IVE.

Table 2
Descriptive Statistics and t-test Results for Negative Affect *In-Situ*.

	Biophilic		Non-biophilic		n	95% Confidence Interval of the Difference	R	t	df	p
	M	SD	M	SD						
Negative Affect	11.73	2.55	12.80	3.93	30	−2.02, −0.11	0.77	−2.28	29	0.03

Note: M – Mean, SD – Standard Deviation.

Table 3
Descriptive Statistics and t-test Results for Negative Affect in IVEs.

	Biophilic		Non-biophilic		n	95% Confidence Interval of the Difference	R	t	df	p
	M	SD	M	SD						
Negative Affect	12.00	2.67	13.53	5.05	30	−2.99, −0.07	0.64	−2.15	29	0.04

Note: M – Mean, SD – Standard Deviation.

4.2. *Positive affect – PANAS*

Similarly, to answer the question, "Does natural element exposure in IVE increase the positive mood of participants in the same way as natural element exposure *in-situ*?", we performed two t-tests. The first t-test compared positive affect data between biophilic and non-biophilic design *in-situ* (Table 4). The second t-test compared positive affect data between biophilic and non-biophilic design in IVEs (Table 5).

The data was visualize using a boxplot (Fig. 13).

The t-test on the data collected *in-situ* (Table 4) showed a statistically significant diffence between biophilic and non-biophlic designs with $p = 0.001$ (two-tailed) at a 95% confidence interval. The mean positive affect (PA) score increased from non-biophilic ($M = 23.90$, $SD = 8.26$) to biophilic ($M = 27.57$, $SD = 8.59$), suggesting that biophilic design increased positive affect *in-situ*.

However, the t-test on the data collected in IVEs (Table 5) did not show a statistically significant difference between biophilic and non-biophilic designs with $p = 0.065$ (two-tailed) at a 95% confidence

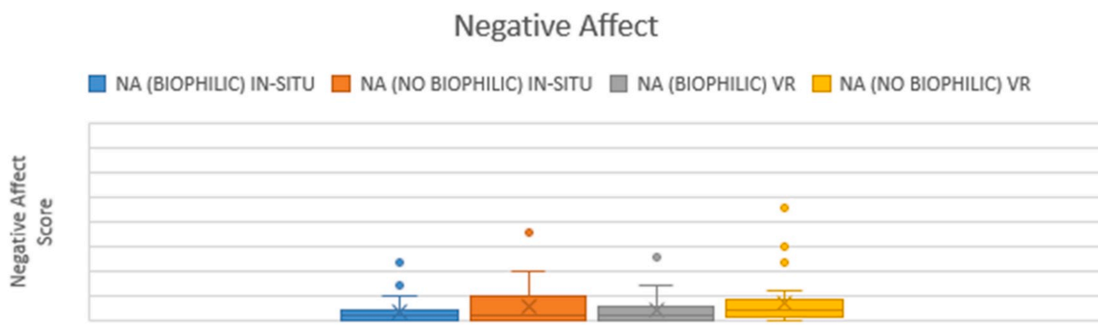

Fig. 12. Negative affect.

Table 4
Descriptive Statistics and t-test Results for Positive Affect in *In-Situ*.

Outcome	Biophilic		Non-biophilic		n	95% Confidence Interval of the Difference	r	t	df	p
	M	SD	M	SD						
Positive Affect	27.57	8.59	23.90	8.26	30	1.74, 5.59	0.81	3.90	29	0.001

Note: M – Mean, SD – Standard Deviation.

Table 5
Descriptive Statistics and t-test Results for Positive Affect in IVEs.

Outcome	Biophilic		Non-biophilic		n	95% Confidence Interval of the Difference	r	t	df	p
	M	SD	M	SD						
Positive Affect	28.97	8.78	26.97	9.32	30	−0.13, 4.13	0.80	1.92	29	0.065

Note: M – Mean, SD – Standard Deviation.

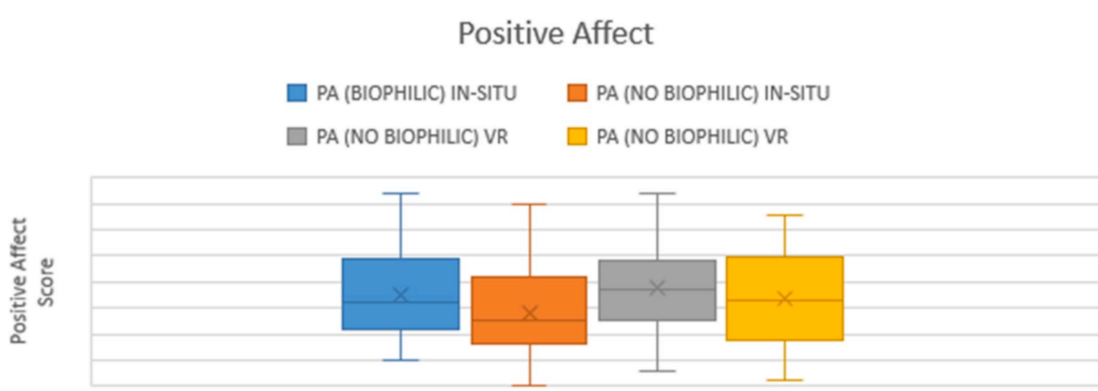

Fig. 13. Positive affect.

interval. Even though the mean positive affect (PA) score increased from non-biophilic (M = 26.97, SD = 9.32) to biophilic (M = 28.97, SD = 8.78), the test result suggests that biophilic design in IVEs did not have the same effect as *in-situ*.

Therefore, although we have observed similar results in the *in-situ* experiment as what has been reported in existing literature (e.g. Ref. [81]), we cannot reject the hypothesis at a 95% confidence interval that the impact of biophilic and non-biophilic designs are the same on positive affect in IVEs. In other words, in IVEs we have not observed a statistically significant increase in positive affect from non-biophilic design to biophilic design. Since we used the same experimental procedure on the same participants in both IVE and *in-situ* experiments, the discrepancy, i.e., an increase in positive affect in the *in-situ* experiment but not in the IVE experiment, is likely related to the experiment setting. Factors associated with the IVE experiment such as the quality of IVEs and participants' experience in the IVE experiment may have played a role influencing participant's positive affect in the experiment.

4.3. *Visual working memory*

To answer the question, "Does natural element exposure have the same impact on the cognitive performance of participants (visual working memory) in both IVE and *in-situ*?", we performed two t-tests as we did for positive and negative affect. The first t-test compared visual working memory performance between biophilic and non-biophilic design *in-situ* (Table 6). The second t-test compared the Visual working memory performance data between biophilic and non-biophilic design in IVEs (Table 7).

The boxplot in Fig. 14 is shows the data distribution of visual working memory tests.

The t-test on the data collected *in-situ* revealed a statistically significant difference between biophilic and non-biophlic designs with p = 0.031 (two-tailed) at a 95% confidence level. The average visual working memory (VWM) percentage corect increased from non-biophilic (M = 81.72, SD = 6.10) to biophilic (M = 84.28, SD = 6.20), which suggests that biophilic design improved visual working memory *in-situ*.

The t-test on the data collected in IVEs did not show a statistically significant difference biophilic and non-biophlic designs with p = 0.599 (two-tailed) at a 95% confidence level, although the mean visual working memory (VWM) percentage correct score increased from non-biophilic (M = 81.72, SD = 6.42) to biophilic (M = 82.33, SD = 5.58). The result suggests that biophilic design did not significantly improve the performance of visual working memory in IVEs, which indicates that IVEs or the experiment process may have played a role influencing participants' performance on this test.

4.4. Stress level

To answer the question, "Does natural element exposure in IVE reduce the stress level of participants in the same way as natural element exposure *in-situ*?", we performed a series of t-tests on heart rate variability measures in the different scenarios. The Kubios software offers a variety of measures for calculating HRV. We chose to use the SNS index and the PNS index. The SNS index measures the sympathetic nervous system (SNS) activity compared to normal resting values; while the PNS index measures the parasympathetic nervous system (PNS) activity compared to normal resting values [82]. The SNS index is calculated based on mean HR (bpm), Baevsky's stress index, and SD2 (%); while the PNS index is calculated based on mean RR (ms), RMSSD (ms), and SD1 (%). Since we are interested in comparisons between IVE and *in-situ* experiments, and between biophilic design and non-biophilic design, the indexes are sufficient.

The following is a set of paired t-tests of the SNS index and the PNS index between *in-situ* and IVE experiment settings, as well as between biophilic design and non-biophilic design.

Tables 8 and 9 showed t-test results of the PNS and SNS indexes between *in-situ* and IVE with respect to biophilic design. The p values (0.32 for the PNS index and 0.75 for the SNS index) in both cases show there is no significant difference at a 95% confidence interval between *in-situ* and IVE experiment settings.

Tables 10 and 11 showed t-test results of the PNS and SNS indexes between *in-situ* and IVE with respect to non-biophilic design. The p values (0.57 for the PNS index and 0.87 for the SNS index) in both cases show there is no significant difference at a 95% confidence interval between *in-situ* and IVE experiment settings.

Tables 12 and 13 revealed t-test results of the PNS and SNS indexes between biophilic and non-biophilic design in the IVE experiment setting. The p values (0.70 for the PNS index and 0.84 for the SNS index) in both cases show there is no significant difference at a 95% confidence interval between biophilic and non-biophilic design.

Tables 14 and 15 revealed t-test results of the PNS and SNS indexes between biophilic and non-biophilic design in the *in-situ* experiment setting. The p values (0.9 for the PNS index and 0.44 for the SNS index) in both cases show there is no significant difference at a 95% confidence interval between biophilic and non-biophilic design.

The t-tests above show that the PNS index and the SNS index are not significantly different in all comparisons. In other words, the previous reported effect of biophilic designs such as inducing relaxation and reducing stress (e.g. Ref. [55,83]) was not observed in both *in-situ* and IVE experiments. Therefore, we cannot determine whether the natural element exposure in IVE has reduced the stress level in the same way as the natural element exposure does *in-situ*.

4.5. Presence

Pairwise t-tests on presence data indicated that in three categories of presence, general (Table 16), spatial (Table 17), and realness (Table 19), there were no significant differences between the biophilic IVE and the non-biophilic IVE. However, there was a statistically significant difference in the involvement category (Table 18) between the biophilic and the non-biophilic design in the IVE experiment setting.

There was not a significant difference in the scores of general presence between biophilic (M = 70.67, SD = 17.21) and non-biophilic (M = 70.67, SD = 19.46) IVEs with p = 1.00 and a 95% confidence interval (Fig. 15) (Table 16).

There was not a significant difference in the scores of spatial presence the biophilic IVE (M = 73.07, SD = 8.85) and the non-biophilic IVE (M = 73.87, SD = 9.02) with p = 0.676 at a 95% confidence level (Fig. 16) (Table 17).

There was a significant difference in the scores of involvement between the biophilic IVE (M = 59.50, SD = 7.47) and the non-biophilic IVE (M = 65.33, SD = 11.29) with p = 0.001 at a 95% confidence level (Fig. 17) (Table 18).

There was not a significant difference in the scores of realness between the biophilic IVE (M = 62.00, SD = 12.43) and the non-biophilic IVE (M = 59.67, SD = 14.62) with p = 0.263 at a 95% confidence level (Fig. 18) (Table 19).

5. Discussions

Our study confirmed that biophilic designs had a positive impact on humans with respect to positive and negative affect and visual working memory performance, i.e., a short-term exposure *in-situ* improved positive mood and the visual working memory of participants and decreases negative mood. This finding is consistent with existing literature (e.g. Ref. [55]). However, following a similar experiment procedure as *in-situ*, we found mixed results in IVE experiments. While biophilic design in IVE experiments showed a similar effect as *in-situ* for negative affect, it did not show significant improvements for positive affect or visual working memory performance. In addition, using the PNS index and the SNS index as measures for stress level, we did not observe any significant differences between biophilic and non-biophilic designs in the *in-situ* or the IVE experiment setting. This result is different from a recent study [55] that found virtual and *in-situ* environments provided comparable results between biophilic and non-biophilic designs.

Many factors can possibly contribute to this outcome. A further analysis of the positive affect data show that there is a significant difference in the data of non-biophilic design between *in-situ* and IVE experiments (*in-situ*: Mean 23.90; IVE: Mean 26.90; p = 0.01, 95% confidence level). However, there is no significant difference in the data of biophilic design between *in-situ* and IVE experiments (*in-situ*: Mean 27.57; IVE: Mean 28.97; p = 0.16, 95% confidence level). This suggests that the relatively high score of positive affect in the IVE experiment related to non-biophilic design causes the discrepancy. However, it is unclear why IVE affects positive affect, but not negative affect.

In the case of visual working memory, it is the difference of performance scores between biophilic and non-biophilic design in IVEs, which contributes to the observed discrepancy between the *in-situ* and IVE

Table 6
Descriptive Statistics and t-test Results for Visual Working Memory *In-Situ*.

Outcome	Biophilic		Non-biophilic		n	95% Confidence Interval of the Difference	r	t	df	p
	M	SD	M	SD						
Visual Working Memory	84.28	6.20	81.72	6.10	30	0.25, 4.86	0.50	2.27	29	0.031

Note: M − Mean, SD – Standard Deviation.

Table 7
Descriptive Statistics and t-test Results for Visual Working Memory in IVE.

Outcome	Biophilic		Non-biophilic		n	95% Confidence Interval of the Difference	r	t	df	p
	M	SD	M	SD						
Visual Working Memory	82.33	5.58	81.72	6.42	30	−1.74, 2.96	0.46	0.53	29	0.599

Note: M – Mean, SD – Standard Deviation.

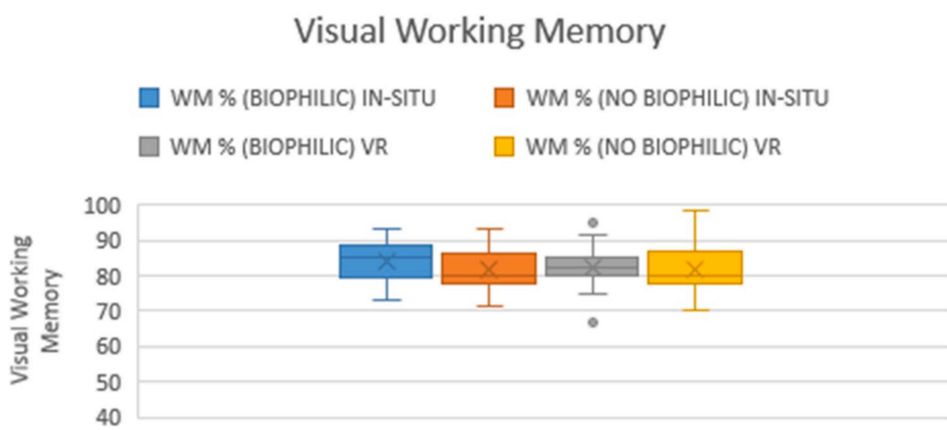

Fig. 14. Visual working memory.

Table 8
Descriptive Statistics and t-test Results for PNS in Biophilic Design.

Outcome	*In-Situ* Biophilic		IVE -Biophilic		n	95% Confidence Interval of the Difference	r	t	df	p
	M	SD	M	SD						
PNS Index	−0.16	1.73	0.24	2.39	26	−1.22, 0.41	0.56	−1.01	25	0.32

Note: M – Mean, SD – Standard Deviation.

Table 9
Descriptive Statistics and t-test Results for SNS in Biophilic Design.

Outcome	*In-Situ* Biophilic		IVE Biophilic		n	95% Confidence Interval of the Difference	r	t	df	p
	M	SD	M	SD						
SNS Index	0.94	1.41	0.86	1.19	26	−0.45, 0.62	0.50	0.32	25	0.75

Note: M – Mean, SD – Standard Deviation.

Table 10
Descriptive Statistics and t-test Results for PNS in Non-Biophilic Design.

Outcome	*In-Situ* Non-Biophilic		IVE Non-Biophilic		n	95% Confidence Interval of the Difference	r	t	df	p
	M	SD	M	SD						
PNS	0.23	2.56	−0.52	2.10	18	−0.74, 1.31	0.63	0.59	17	0.57

Note: M – Mean, SD – Standard Deviation.

Table 11
Descriptive Statistics and t-test Results for SNS in Non-Biophilic Design.

Outcome	*In-Situ* Non-Biophilic		IVE Non-Biophilic		n	95% Confidence Interval of the Difference	r	t	df	p
	M	SD	M	SD						
SNS	0.83	1.54	0.79	1.14	18	−0.48, 0.56	0.74	0.17	17	0.87

Note: M – Mean, SD – Standard Deviation.

experiment settings. The t-tests in Tables 7 and 8 show that the difference between biophilic design and non-biophilic design *in-situ* is 2.27 percent. It is 0.53 percent in the IVE. Apparently, biophilic design in IVEs may improve visual working memory, but not as effective as *in-situ*. Further research is needed to better understand the factors that may affect the extent to which visual work memory tests may be improved in

Table 12
Descriptive Statistics and t-test Results for PNS in the IVE Experiment Setting.

Outcome	IVE Biophilic		IVE Non-Biophilic		n	95% Confidence Interval of the Difference	r	t	df	p
	M	SD	M	SD						
PNS	0.60	2.60	0.75	2.89	27	−0.97, 0.67	0.72	−0.38	26	0.70

Note: M − Mean, SD – Standard Deviation.

Table 13
Descriptive Statistics and t-test Results for SNS in the IVE Experiment Setting.

Outcome	IVE Biophilic		IVE Non-Biophilic		n	95% Confidence Interval of the Difference	r	t	df	p
	M	SD	M	SD						
SNS	0.76	1.17	0.79	1.11	27	−0.31, 0.26	0.80	−0.20	26	0.84

Note: M − Mean, SD – Standard Deviation.

Table 14
Descriptive Statistics and t-test Results for PNS in the In-Situ Experiment Setting.

Outcome	*In-Situ* Biophilic		*In-Situ* Non-Biophilic		n	95% Confidence Interval of the Difference	r	t	df	p
	M	SD	M	SD						
PNS	0.14	2.66	0.22	2.36	22	−1.40, 1.24	0.30	−0.12	21	0.9

Note: M − Mean, SD – Standard Deviation.

Table 15
Descriptive Statistics and t-test Results for SNS in the In-Situ Experiment Setting.

Outcome	*In-Situ* Biophilic		*In-Situ* Non-Biophilic		n	95% Confidence Interval of the Difference	r	t	df	p
	M	SD	M	SD						
SNS	0.86	1.58	0.70	1.48	22	−0.27, 0.60	0.79	0.78	21	0.44

Note: M − Mean, SD – Standard Deviation.

Table 16
Descriptive Statistics and t-test Results for General Presence in IVE.

Outcome	Biophilic		Non-Biophilic		n	95% Confidence Interval of the Difference	r	t	df	p
	M	SD	M	SD						
General	70.67	17.21	70.67	19.46	30	−6.79, 6.79	0.51	0.00	29	1.00

Note: M − Mean, SD – Standard Deviation.

Table 17
Descriptive Statistics and t-test Results for Spatial Presence in IVE.

Outcome	Biophilic		Non-Biophilic		n	95% Confidence Interval of the Difference	r	t	df	p
	M	SD	M	SD						
Spatial Presence	73.07	8.85	73.87	9.02	30	−4.67, 3.07	0.33	−0.42	29	0.676

Note: M − Mean, SD – Standard Deviation.

Table 18
Descriptive Statistics and t-test Results for Involvement Presence in IVE.

Outcome	Biophilic		Non-Biophilic		n	95% Confidence Interval of the Difference	r	t	df	p
	M	SD	M	SD						
Involvement	59.50	7.47	65.33	11.29	30	−9.05, −2.62	0.65	−3.70	29	0.001

Note: M − Mean, SD – Standard Deviation.

IVE experiments as in *in-situ* experiments. These factors can be related to virtual environment design or participants (e.g., their sensitivity to virtual environments).

In addition, our study followed a similar data collection measure as in another study [55], but found that heart rates did not change significantly between biophilic and non-biophilic designs in *in-situ* or

Table 19
Descriptive Statistics and t-test Results for Realness Presence in IVE.

Outcome	Biophilic		Non-Biophilic		n	95% Confidence Interval of the Difference	r	t	df	p
	M	SD	M	SD						
Realness	62.00	12.43	59.67	14.62	30	−1.85, 6.51	0.67	1.14	29	0.263

Note: M – Mean, SD – Standard Deviation.

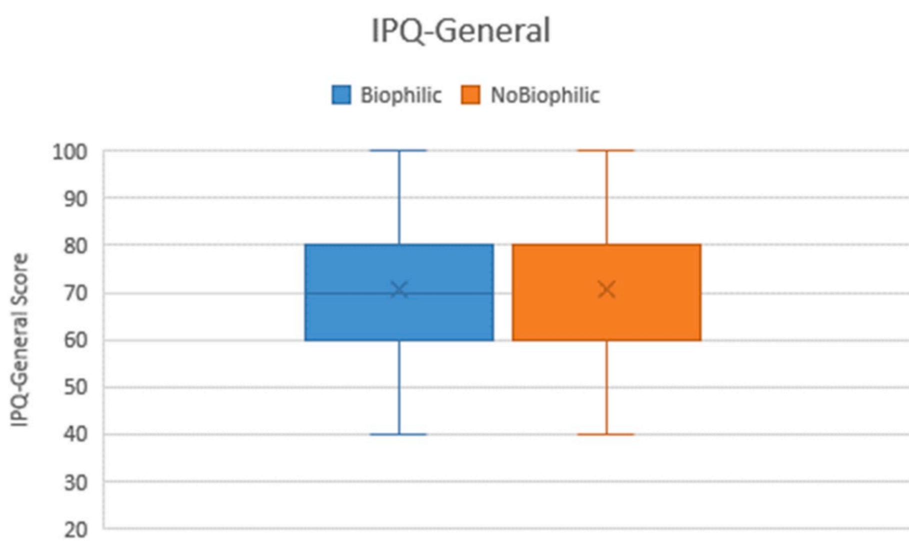

Fig. 15. Ipq general.

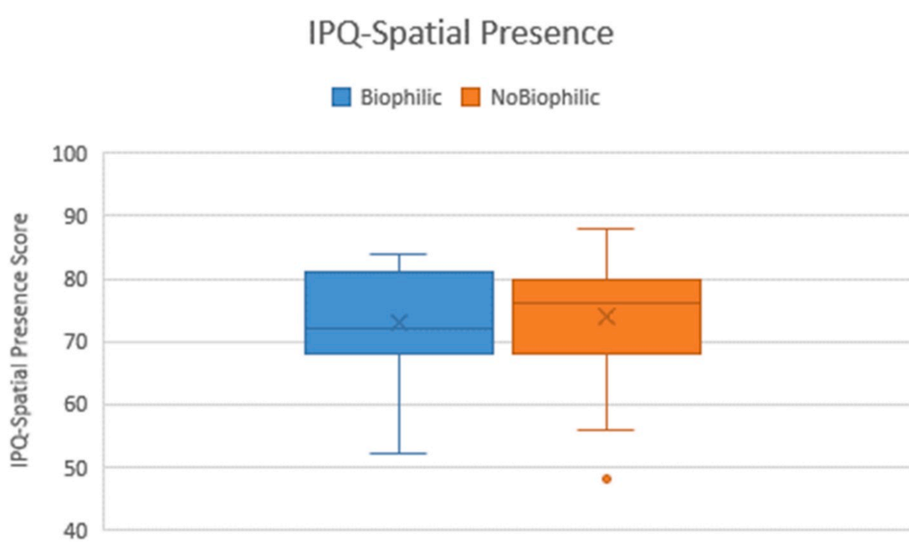

Fig. 16. IPQ-spatial presence.

IVE experiments. This result is also different from general theories such as the Stress Recovery Theory, which states that exposure to natural elements can impact the parasympathetic system and decrease the heart rate. The inconsistency between our findings and the Stress Recovery Theory [84] suggests that elements of the experiment procedure and the virtual experimental design, such as the exposure time to nature (both *in-situ* and in IVEs) and the design of virtual stimuli, may impact this effect. In addition, there is also a possibility that the differences in heart rate may be more observable only during a specific time period, such as during the time of exposure only. These ideas suggest that a standard data collection and analysis procedure is necessary.

The presence test revealed that the IVEs for biophilic design and non-biophilic design were in general comparable in terms of spatial, realism, and general presence. However, the IVE for non-biophilic design had a higher involvement presence than that for biophilic design. Since the involvement presence measures participants' attention to virtual environments, this could be a factor that contributes to the discrepancy in both positive affect and visual working memory. In addition, we learned that the level of model details had an impact on participants' feeling towards IVEs. For example, we used a video of the real world in the design of the biophilic immersive virtual environment. Some participants reported that the contrast between the overall model and the video distracted them. In another example, one participant mentioned that he felt a sense of disorientation and did not feel connected in the biophilic

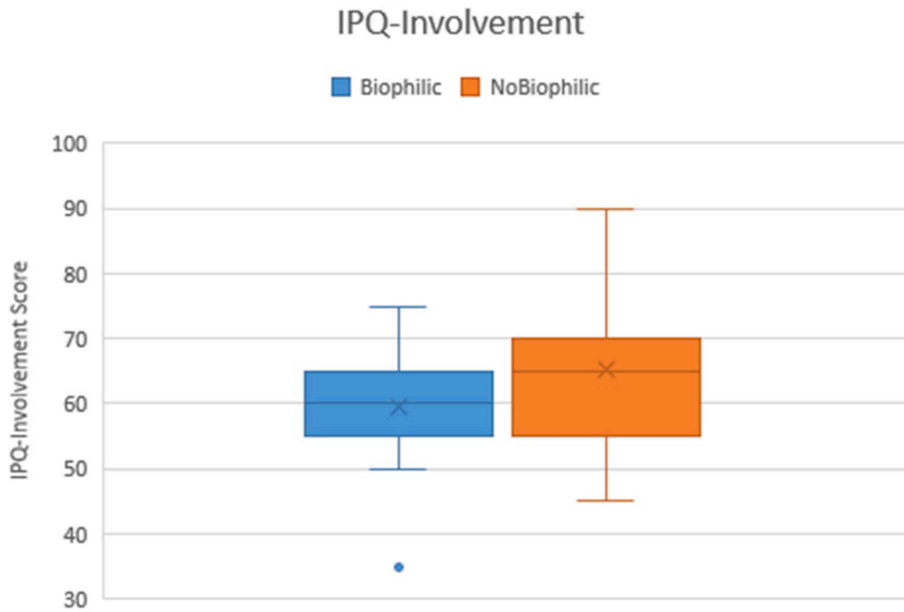

Fig. 17. IPQ-involvement.

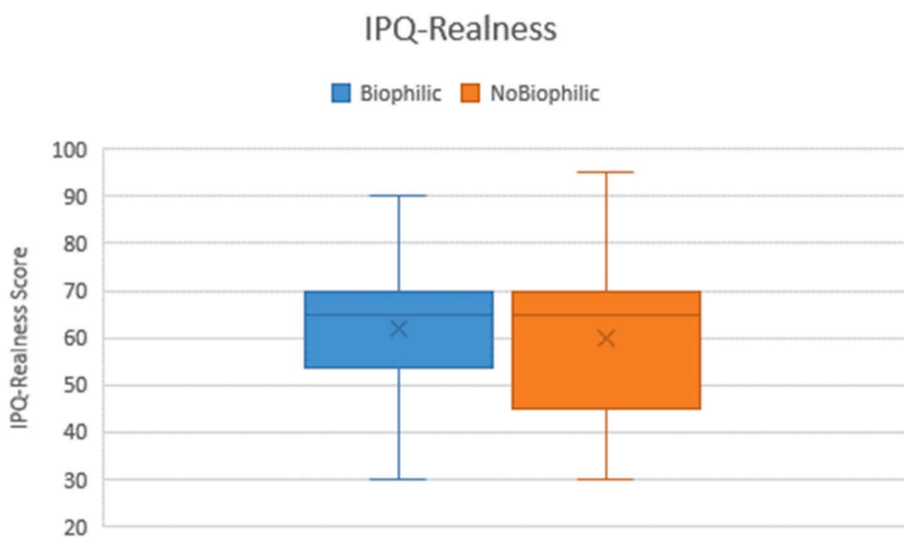

Fig. 18. IPQ-realness.

IVE, because it was a rainy day when the participant was doing the IVE experiment, but the IVE showed a sunny day. The participant said this disconnection between reality and the IVE made the IVE for biophilic design less realistic for him. The participant also said that in the non-biophilic environment, the IVE was very similar to the actual environment so he did not feel disconnection in the non-biophilic environment. Thus, it is very likely that participants' sense of immersion and presence, as well as other psychological responses to virtual environments can impact the results. However, the extent of such an impact is not yet known.

6. Conclusions and future studies

Applications of immersive virtual environments to building design, including biophilic design, are still in their infancy. There are many factors affecting the success of such applications, which has led to the mixed results of this study. While we find the potentials of IVE applications to biophilic design, factors associated with the design of virtual stimuli, experimental procedure, and the characteristics of participants may affect the results of experiments. It is necessary to determine the practicality of replicating some biophilic elements in lab settings, e.g., IVE experiments. For example, at this time we don't know the threshold of exposure time to nature for different demographic groups or virtual stimuli, in order to discern the effect of biophilic design in immersive virtual environment. More time than what was used in the current study may be necessary. On the other hand, if the exposure time is too long, it may not be practical to conduct such a study in a lab or IVE setting. Therefore, there is still a significant amount of research needed to determine the exposure time before IVEs can be effectively used to replicate *in-situ* biophilic features for scientific experiments.

Future studies should focus on the impact of IVEs on design by systematically including experimental procedures, tools and instruments applied in experiments, as well as the type of participants. The importance of experimental procedure is reflected in this study. For example, the exposure duration to biophilic elements in IVEs may impact the results of visual working memory experiments. Tools such as virtual environments or virtual stimuli and instruments such as questionnaires for data collection play a significant role in developing a reliable experiment protocol. For example, collecting PANAS data before an experiment could allow the data to be used as a baseline to compare with PANAS data collected after experiments. Determining when and what data collection instruments to include is important because it is related to the design of an effective experiment protocol. Finally, participants are critical to the quality of research. The presence test shows that how people feel about virtual environments can affect the outcome of research.

In this study, stress level, cognitive performance, and self-reported mood are treated as three variables to measure the benefits of biophilic design. However, the cross-influence of the three variables is not known. Questions such as if stress level impacts cognitive performance or mood need to be explored in the future.

Declaration of competing interest

There is no conflict of interest.

CRediT authorship contribution statement

Asalsadat Emamjomeh: Conceptualization, Methodology, Investigation, Formal analysis, Writing - original draft. **Yimin Zhu:** Supervision, Resources, Writing - review & editing. **Melissa Beck:** Supervision, Writing - review & editing.

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Appendix A. Supplementary data

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