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Artificial Intelligence Evaluates How Humans Connect to the Built Environment: A Pilot Study of Two Experiments in Biophilia

Tobias M. Ramm [1], Mathias Werwie [1], Tim Otto [1], Peter A. Gloor [1,2,3,*] and Nikos A. Salingaros [3,4]

1 Cologne Institute for Information Systems (CIIS), University of Köln, Pohligstraße 1, 50969 Cologne, Germany; tramm2@smail.uni-koeln.de (T.M.R.); mwerwie@smail.uni-koeln.de (M.W.); totto3@smail.uni-koeln.de (T.O.)
2 MIT Center for Collective Intelligence, Cambridge, MA 02142, USA
3 Galaxylabs, Laurenzenvorstadt 69, 5000 Aarau, Switzerland
4 Departments of Mathematics and Architecture, University of Texas at San Antonio, One UTSA Circle, San Antonio, TX 78249, USA; salingar@gmail.com
* Correspondence: pgloor@mit.edu

Abstract: Many factors influence well-being and health in everyday life. While people are aware of traffic delays or continuous work stress, other factors influence the state of the body on a subconscious level. The built environment subconsciously influences human physiology during every second of life, which has a cumulative long-term effect. The idea of biophilic design identifies the importance of natural elements implemented in architectural structures to improve the occupants' health and well-being. This paper measures the impact of biophilic design on positive emotions and productivity in two separate but conceptually related pilot studies that apply novel approaches: (a) facial emotion recognition (FER) with residual masking networks and (b) sentiment detection using Large Language Models. The first study measures the emotions of people when confronted with images of different kinds of architecture, via FER and via a user survey. We find clear trends for emotions detected by FER and significant evidence for self-stated emotions that architecture implementing biophilic design evokes more positive emotions. The second study measures the influence of natural elements on productivity and team engagement. The findings show that natural elements in the surroundings do influence productivity and sentiment positively. As the sample size of subjects, especially for the second study, was relatively small, future research will need to apply these ideas in a larger setup to acquire further evidence for the importance of biophilic design for human well-being and health.

Keywords: biophilic design; biophilia; well-being; health; built environment; facial emotion recognition (FER); large language models for sentiment detection; architectural impact on emotions

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1. Introduction—Biophilic Healing Properties

1.1. Biophilic Environments—Both Natural and Artificial

Biophilia refers to the inherent and deep-seated human love and connection with the natural world [1]. This feeling, an unconscious experience that everyone can relate to, especially when being immersed within a natural environment, is the root behind the concept of biophilic design. In an age characterized by rapid urbanization and the pressing challenges of climate change, designing environments that foster human happiness and productivity has never been more critical. Biophilic design aims to establish a profound and positive connection between people and the built environment. Drawing inspiration from the effect of biophilia coming directly from nature, this design approach seeks to integrate natural elements and patterns into urban spaces, work areas, and homes. This paper explores the positive impact of biophilic concepts on the human psyche and cognition. Two pilot studies investigate the biophilic influence on the conscious (Study 1) and subconscious mind (Study 2), measuring the effect of biophilic principles on human emotion and cognition indirectly (Figure 1).

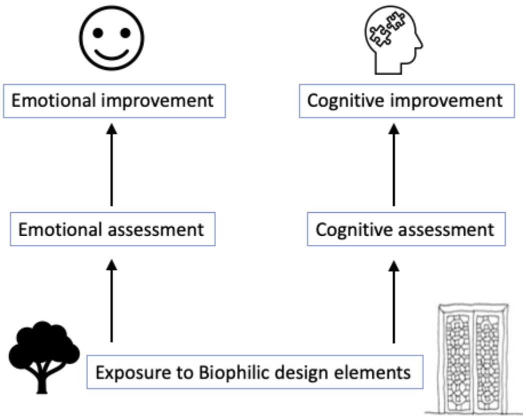

Figure 1. Framework of pilot studies to demonstrate positive impact of biophilic qualities.

In addition to direct biophilic stimulation from nature, the human body perceives and recognizes artificial structures that embody the complex mathematics of nature. However, most people are unaware of the geometry of the built environment in any conscious sense, even though their body is reacting strongly to it. Therefore, human artifacts and the built environment can exert a positive biophilic effect if they are designed in a particular way. The desired positive result is due not so much to the simple mimicking of natural forms, which is a superficial effect, but rather to using those same generative processes that nature uses in order to create the built environment [2–4].

Parallel streams of ongoing research investigate how biophilic environments contribute to human health and well-being. This topic is still developing and has not yet coalesced into a single discipline. Distinct strands of investigations look at physiological and psychological changes (usually for the better) when a human subject is situated in a natural environment. The health benefits of being in or exposed to a natural environment are documented in numerous studies [5,6]. The literature lists the health benefits of nature exposure accepted in traditional cultures. A separate train of research investigates unconscious reactions of human subjects to different environments, both natural and artificial. A subjective evaluation of places by pedestrians uses portable monitors to register the emotional and physiological reactions to the urban environment, with results showing marked variation from one spot to another [7]. It has been conclusively shown that positive reactions occur in what can be characterized either biologically or mathematically as strongly biophilic settings [8,9].

The desired objective of this research is to encourage the creation of salutogenic environments, rather than merely "efficient" ones from the point of view of the construction and transportation industries. Not only will this goal help to improve human health but it could drastically boost sustainability. A major yet low-cost contribution to sustainability is for environments and places to be appreciated by their occupants, often for reasons that are not consciously evident [10,11]. The link to sustainability is indirect and follows the postulate that environments that follow biophilic design are more sustainable. It is not our purpose to develop this argument further here, but we note that highly biophilic settings are among the most sustainable artificial and natural environments.

Biophilic environments are loved because people feel comfortable in them and will maintain them much more readily than industrial environments that are hated because they are perceived as neutral or even hostile. This "likeability" factor plays a major role in how cities develop, although it is insufficiently discussed in the literature. A serious obstacle to investigation is that people usually cannot identify the source of their psychological sense of well-being (or its opposite, unease), even when such emotions are being triggered by geometrical details in their environment. Sensor systems in "smart" cities are helping to expand the opportunities of real-time feedback to answer questions of likeability linked to use [12,13]. Sustainable development strategies for smart cities therefore need to address this as one primary aspect of society maintaining its built fabric.

1.2. Using Artificial Intelligence in Measuring Positive Responses to Environments

The term AI (Artificial Intelligence) in the title of this paper refers to the experimental tools employed to measure the positive biophilic effect on subjects. The studies reported here try to ascertain how people feel in different environments that have different degrees of biophilia, estimated quantitatively by how many components of biophilic design they possess. In departing from the usual questionnaire and conscious statements, we used two distinct AI tools to measure the subjects' reactions indirectly, without their conscious input. Our experiments focus on the subjects' emotions and productivity. We believe that this indirect method, made possible only through recent technical developments, overcomes a long-standing problem of mixing objective with subjective subject responses. This point is discussed further in the Discussion section, below.

1.3. Addressing Different Scales of Architectural Spaces

Biophilic concepts can be applied on different granularity levels of architecture spaces. They will have a large-scale impact on the urban level, but they will also be positively experienced by the individual in the home and work environment. The most desirable result occurs when many different built scales, ranging from the very small to the largest, all possess biophilic qualities. As in nature, all the scales contribute. If the design and construction follow biophilic principles, then the result will be perceived as coherent even though the visual information is complex.

Urban spaces: As the world's population increasingly moves towards cities, the dominance of concrete landscapes demolishes our natural surroundings. This rapid urbanization has given rise to "nature deficit disorder" [14], where the lack of interaction with nature contributes to declines in physical and mental health. Children's healthy development is especially affected. Biophilic design offers hope to improve urban environments by providing a way to reintroduce nature, and artificial surrogates of nature, into our lives. Urban spaces that incorporate biophilic effects through their design are more healing to their users [10].

Work areas: Recognizing that the well-being and productivity of employees directly influence organizational success, biophilic design also presents an opportunity to transform traditional office spaces. Biophilic design is likely to create an environment that promotes creativity, reduces stress, and enhances cognitive performance [15,16]. Through the inclusion of indoor plants, natural light, and other biophilic elements, workplaces can offer a significant positive impact on overall happiness and job satisfaction for the workforce that experiences them. In contrast, by neglecting the fundamental need for human connection with nature, those who work in today's minimalist, "industrial design" workplaces may experience decreased morale, elevated stress levels, and reduced productivity.

Homes: Mental health issues have become a pressing concern in the modern world. The healing power of nature is well documented [17–19], and biophilic design utilizes this salutogenic effect to create spaces that aid in reducing anxiety, depression, and stress-related disorders. In a separate direction of research, the central role of informationally rich interiors in helping the developing child to develop its intelligence is beginning to be investigated by the present authors and others.

1.4. Biophilic Design Qualities

The degree or intensity of a particular setting's biophilic attributes can be estimated by looking at different factors that contribute to the biophilic effect on humans. It is instructive to point out that, because this is a developing topic, different authors look for slightly different qualities, yet agree overall [20]. Below, we present a listing of biophilic qualities by one of the co-authors, whose effect can be easily gauged. The biophilic qualities combine natural elements together with geometrical properties of the environment. These factors were distilled from the mathematics of organic forms, which prompted the evolution of the human brain so as to interpret environmental information for survival. In addition, some properties, such as sunlight, color, gravity, fractals, curves, detail, water, life, representation of nature, and organized complexity, relate more deeply to the physics of complex systems [21,22].

Biophilic design is an approach that emphasizes incorporating natural elements and patterns into the built environment to improve human well-being. It aims to reduce stress, enhance creativity, and accelerate healing. Previous research explores the relationship between nature, human biology, and design to exploit the benefits of biophilia in architectural applications. Note how, of the above biophilic qualities, sunlight, gravity, water, and life come from being in contact with nature, whereas the biophilic qualities of color, fractals, detail, and organized complexity can either occur naturally or be created artificially. The biophilic quality "representation of nature" is strictly artificial. Laying the foundations of our understanding of biophilic design has been the main inspiration and guidance for this project.

In order to understand our project and our study preparations as well as decisions, it is necessary to subsequently introduce each biophilic design group and their respective components. The terminology of Terrapin Bright Green [3,20] was found convenient for our discussion and so their equivalent terms are listed below in brackets. Since the experiments reported here depended primarily on the visual quality of the settings, we will not describe other biophilic factors such as aural, haptic, or olfactory, which also influence the human senses unconsciously. We have tried to help readers who may be familiar with either of two separate listings of biophilic criteria referring to similar concepts, but which are labeled with different titles, by listing double titles corresponding to [3,20].

1.5. Life (Nature in the Space)

Nature refers to the tangible presence of living and natural elements like plants, water, and animals (including other humans). Examples of this quality in artificial environments can be seen in potted plants, flowerbeds, water features, and green walls. Adding to this biophilic component is humankind's millennial love of domestic animals and, in rural communities, close contact with farm animals. The most impactful experiences of nature in a space are created when people establish meaningful and direct connections. Additional biophilic elements can be further categorized into *Life, Water*, and *Sunlight*. Life and visual connection with nature include the view of natural elements or living systems (e.g., plants). Water or the presence of water includes seeing, hearing, or touching water (e.g., a water fountain). Sunlight, and dynamic and diffuse light represents varying light usage and intensity (e.g., sunlight and firelight).

The biophilic effect occurs because humans try to connect to the built environment in the same way that they connect to the natural environment. Neurophysiological mechanisms evolved to interpret environmental information rapidly (unconsciously) and correctly to ensure individual and eventually species survival. The existing research on biophilia focuses so far on natural forms and geometries, yet this initial, intuitive concept is expanding to include the effects of artificial geometries that mimic natural ones. The advantage in interpreting a place in terms of its biophilic qualities is that it can be analyzed using objective criteria. There are no disadvantages of biophilic interpretation, unless the design profession realizes that some of its preferred modalities and typologies are not very biophilic and should be discarded [23–26].

1.6. Representations of Nature (Natural Analogues)

Natural analogues in design involve using non-living objects, colors, shapes, and patterns found in nature to evoke a natural feeling in the built environment. This includes art-work, furniture, ornament, and textiles inspired by natural forms. For example, furniture with shapes resembling shells or leaves, and using processed natural materials like wood planks or granite tabletops perform this function. The evolution of humans progressed alongside sophisticated ornamental traditions, in which artifacts mimicked abstracted natural forms. While these items are not an actual part of nature itself, they can help establish a biophilic connection. Ornament includes *Representations of nature (Biomorphic Forms and Patterns)* which are textures and patterns similar to natural occurrences (e.g., tree-shaped columns). These biophilic qualities also include *Fractals and Detail (Material Connection with Nature)* which are minimally processed natural materials (e.g., wood- and stonework). The final biophilic quality in this category is *Organized Complexity (Complexity and Order)* including complex structures similar to natural ones (e.g., exposed organic and inorganic structures).

1.7. Spatial Configurations That Evoke Ancestral Settings

The nature of space in design focuses on how spatial arrangements can evoke feelings and behaviors similar to those experienced when situated in natural environments. This includes people's yearning to have open views, fascination with mystery and discovery, and even feelings of fear mixed with a sense of safety. The most powerful experiences in this context come from intentionally designing spaces that combine engaging spatial layouts with patterns of nature and natural analogues. These latter spatial qualities are not related to the small-scale mathematical structure in objects or surfaces, but to the larger-scale spatial configuration of the lived environment. Such criteria were derived by Christopher Alexander as design patterns (before biophilic design was established as a discipline) and investigated by evolutionary anthropologists and geographers. Jay Appleton coined the "prospect-refuge" theory [27–29]. Rewritten as a summary, Alexander's Pattern 114 describes: "Satisfy the feeling of having one's back protected by a solid structure (refuge), while being able to see out to the world (prospect)" [30]. Qualities in this category include *Prospect*, i.e., a long-distance view for surveillance that is essential for planning subsequent actions and movement. They also include *Refuge*, i.e., a place of protection and withdrawal, and finally *Mystery*, i.e., partially obscured views that promise more information but do not present any obvious threat.

Some investigators and even some architects include the quality *Risk/Peril*, i.e., a threat combined with a reliable safeguard (e.g., infinity edges), as being related to biophilia. Nevertheless, we classify it within the opposite biophobic factors since it triggers a fight-or-flight response. We do not wish to confuse our experimental findings by mixing negative with positive valence responses.

1.8. Existing Research on the Biophilic Effect

Biophilia has a significant impact on how the built environment affects happiness, health, and the productivity of humans. Rhee et al. (2023) [17] investigated the influence of indoor vegetation density on human well-being, with the goal of promoting a healthy built environment. The results reveal that increased greenery in indoor spaces positively affected mood, reduced stress levels, and improved overall well-being, thus supporting the principles of biophilic design.

One of the co-authors [31] investigated the relationship between happiness and biophilic urban geometry, showing the negative impact of modern architecture on user happiness. Neuroscience experiments have been proposed to verify the geometry of healing environments, a direction of research that reinforces the importance of biophilic design in creating healing spaces. Diagnostic tools are currently being developed to achieve this task, and to ultimately identify aspects in architecture that are perceived as beautiful and therefore might influence people's health positively.

Similarly, Darby et al. (2019) [32] propose another human-centered approach in sustainable building design to increase the overall occupant's happiness and concentration considering lighting, smell, and air quality. Allen et al. (2015) [18] conducted a comprehensive study on a framework to measure the impact of green buildings on occupant health. They discovered that green buildings positively influence the occupant's health and, through this, their well-being. Benchmarks for green buildings incorporate controls for increased ventilation, use of materials, indoor air quality monitoring, lighting, exposure to daylight, and views. Hu et al. (2021) [33] investigate how sustainable buildings affect people's thinking and mental well-being compared to conventional buildings. They measured brain activity to understand this impact and suggest that a sustainable building environment improves the focus and processing of the occupants.

The rapidly growing number of these research papers suggests the rising importance of this topic. Many publications target the impact of biophilic design on health and it is undeniable that health influences personal well-being, which in turn helps to boost both happiness and productivity. Nevertheless, this topic is only indirectly related to our target of measuring the impact of biophilic design on happiness and productivity.

2. Methods

All of this evidence motivates research on why biophilic design can be so impactful on individuals and society alike. This paper introduces two separate but related pilot studies that investigate the positive effect. The first experiment—Study 1—measures the emotions that people express when confronted with different kinds of architectural imagery. We chose example pictures representative of building environments with an abundance of biophilic design characteristics, while others show few characteristics or none. Through this comparison we hope to generate an insightful analysis that supports the existing research with quantitative as well as visual results. To the best of our knowledge, applying AI to correlate personal assessments of biophilic attractiveness with unconscious facial expressions is novel.

The second experiment—Study 2—tested how people perform differently according to the biophilic quality of their immediate environment. Since the biophilic effect is salutogenic, then performing a mental task in an environment that decreases stress should influence a person to perform better. We assess productivity and engagement in a team, depending upon how much the environmental setting incorporates natural elements or is even situated in a natural space. Again, we are able to apply AI in an innovative manner (distinct from our first experiment) to extract unconscious information on the subjects' feelings through analyzing their conversations while performing a mentally intensive task. The link between salutogenic environments and their degree of biophilic qualities has been well documented [34]. In previous experiments with biophilia, physiological indices show improved subject health as compared to equivalent settings that lack biophilic qualities [34,35].

Key biophilic design qualities discussed in the previous section are applied and tested experimentally. The two studies will be described, analyzed, and assessed in the following sections. While the two experiments reported here could have been presented separately, they are in fact complementary. Their logical combination provides compelling evidence for how humans connect to the built environment, with either negative or positive consequences depending on its lack or abundance of embedded biophilic properties. Technically, the two methods employed for measuring subject responses to biophilic factors in the environment are distinct. They complement each other by representing two separate aspects of human behavior and emotions that can be measured unobtrusively. We believe that these pilot studies open up future directions of research in using indirect measurements that sidestep complications due to subjective responses because of prior exposure and training. The reason is that the biophilic effect is entirely unconscious; hence, the best way to measure it is through equally unconscious processes.

2.1. Study 1—Impact of Biophilic Design on Emotional Responses

This section explores the emotions evoked in individuals when they are confronted with different intensities of biophilic design in architecture. Numerous studies have highlighted the potential health benefits of incorporating biophilic designs into architectural structures. The present study (combining two experiments) aims to add a new dimension to this research. To understand the depth of the impact of biophilic design elements on individuals, we pose the following research question:

Does biophilic design in architecture trigger more positive emotions?

2.1.1. Study Design

Taking advantage of the progress in artificial intelligence (AI) research in recent years and the resulting improvement in facial emotion recognition technology, we developed an experimental setup in which participants were presented with a curated selection of images, containing different densities of biophilic design elements. The best way to effectively capture as many emotional reactions as possible was by implementing a web application. The easy shareability of a web application ensured that we were able to reach a critical number of participants without having to conduct the experiment in person.

In this application, participants are presented with one image at a time (Figure 2). For each image, they entered one of 3 possible reactions as to how they feel (emotionally, not intellectually) about the architecture of the image: negative, positive, or neutral. This click-reaction survey forms the self-assessment component of the study. While the participants click through the images we simultaneously capture their facial expressions via a webcam, to later extract the emotions using facial emotion recognition, which builds the actual emotional reaction component of the study.

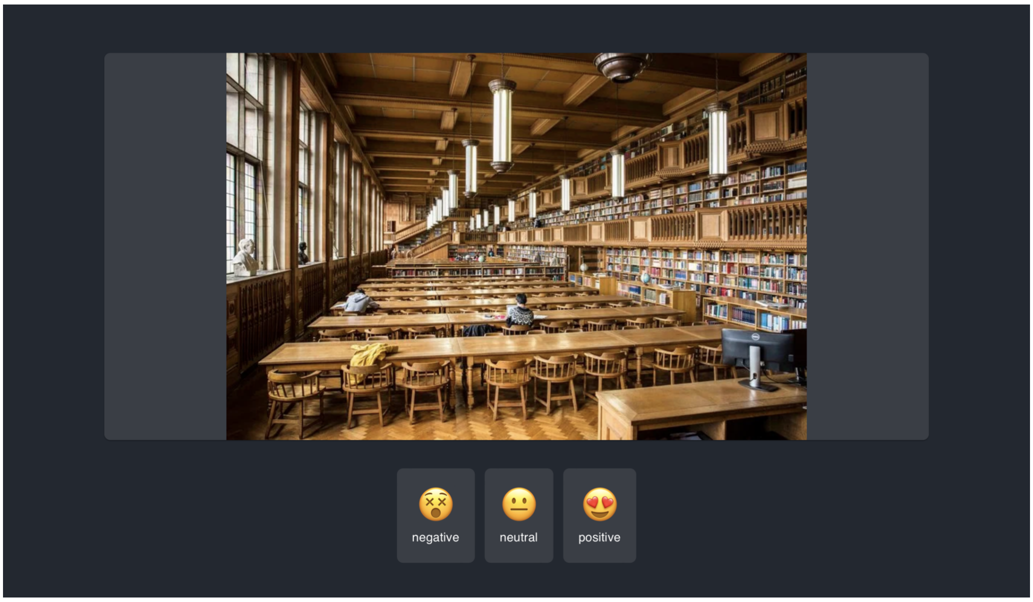

Figure 2. Slideshow view of the FER web application.

For the image selection we distinguished among three picture categories: architecture that does not implement any biophilic design, architecture that implements merely a few components, and architecture that is clearly driven by biophilic design. Furthermore, we want to include every biophilic design pattern by Browning et al. [20] at least once in architecture that we chose to use for this study. The final choice of pictures and a table with the respective biophilic design patterns can be found in Appendix A (Table A1, Figure A1). In total, there are 15 pictures, five for each picture category (corresponding to three different degrees of biophilic content), from a diversity of contexts such as offices, hospitals, libraries, and train stations. Through this we intended to get more generalized results, independent of the type of architecture portrayed. For the same reason, we chose to show a mixture of building façades and building interiors.

The study was conducted over two weeks and involved 39 participants, all residing in Germany. The majority (32 out of 39) fell within the age range 21 to 30, with the most prevalent occupations being student (14), followed by work in the education (7) or information technology sectors (6). Age ranges of 10–20, 31–40, and 61+ all included two participants each, while only one participant fell within the range of 51–60. Other notable occupations of participants were business and finance (4), as well as engineering, sales and marketing, administrative, and healthcare with one participant each. This distribution is reflective of our deliberate recruitment from our immediate surroundings.

2.1.2. Study Execution

We developed the web application using React, an open-source JavaScript Framework initially developed by Facebook [36]. The structure is very simple. The participants had to enter their age range and professional background, and to allow us to access their personal webcam. We used the package React-webcam to take a picture via the subject's webcam every second during the experiment [37]. After the user had reacted to every picture, we uploaded the data to Firebase. This is a cloud-service from Google that provides all necessary functionalities for the development of web and mobile applications, e.g., databases and hosting options [38].

2.1.3. Data Processing

Experimental data were first processed by extracting the facial emotions with the open-source software package py-feat [39], which uses a residual masking network proposed by Pham et al. [40]. For every picture we obtained 7 emotions—anger, disgust, fear, happiness, sadness, surprise, neutral—with each assigned a percentage of its probability.

We grouped all webcam picture reactions by the picture that was shown at that time on the web application and took the average over all emotions. Finally, for every participant, we collected the age, professional category, and, for every picture, the average facial emotion and the clicked emotion.

2.2. Study 2—Influence of Biophilic Design on Productivity and Team Engagement

The second experiment examines the broader impacts of biophilic characteristics on productivity and team engagement. We explored whether the presence of natural elements in a work environment foster better productivity and engagement levels among team members and generally result in better well-being. We investigated the following research question:

Can the presence of biophilic design elements in a work environment enhance productivity, team engagement, and overall sentiment?

2.2.1. Study Design

The second study had to be carried out in person to accurately capture the differences between productivity, team engagement, and sentiment. Due to time and resource restrictions we decided to distinguish only between two different places with opposite biophilic characteristics from each other. The first place chosen was the university meadows on a sunny day, i.e., a very green, spacious, and bright place. The second place was a study room in the canteen, a narrower, nested, dark room consisting of grey walls that has few windows and is therefore mainly artificially lit. We conducted the study with five groups, each consisting of three people. The groups alternated between starting at the outside or inside locations. The weather conditions were similar on each day of the experiment.

The study encompassed 15 participants, all University of Cologne students, whose ages ranged from 20 to 26, averaging 22.8 years. The participants are all native Germans, yet their geographic origins vary from across Germany before coming to study in Cologne. Educational backgrounds exhibited diversity, with 4 participants pursuing bachelor's degrees and 11 engaged in master's programs. Although specific details regarding ethnicity were not collected, given the German context, it is reasonable to infer that participants predominantly identified as Christian or atheist. Among the participants' interests, 10 focused on Information Systems, while others pursued various study disciplines at the

University of Cologne. A concerted effort was made to achieve gender balance among the participants.

2.2.2. Study Execution

To measure the productivity and stimulate communication we used a digital version of the game "memory" (popular in Europe) [41]. First, each group member played one solo game, followed by a game played by the team as a whole. This process was repeated at both locations. Through this exercise we could obtain the number of moves and time needed until completion. In addition, we recorded the conversation during the group game to extract spoken words, speaking activity, and detected sentiments for every speaker. Moreover, we asked every participant upon arrival at the study location to rank their current well-being on a scale from 1–10.

2.2.3. Data Processing

While the metrics obtained from the game and the stated well-beings were already structured for analysis, we had to process the recorded conversations to extract the unconscious mood. The first processing task we performed was speaker diarization, which is the task of partitioning an audio stream into homogeneous temporal segments according to the identity of the speaker, using pyannote.audio [42,43]. We then used OpenAI's WhisperAI Model [44] to transcribe the audio files and afterwards matched the transcript with the result of speaker diarization using timestamps. To ensure that the speaker diarization did not mix up the order between the speakers, we asked the participants to briefly introduce themselves before each group game in the same order, so that we had assignable audio data to identify each participant. After having determined the sequence and content of individual contributions, we proceeded with the final step of the data processing. For each sentence we extracted the sentiment using the Natural-Language-Processing (NLP) Model germansentiment. The base of this model is Google's Large Language Model Bard, which was fine-tuned on 1834 million German-language samples by Guhr et al. [45]. The output is a percentage of the three sentiment categories: (A) positive, (B) negative, and (C) neutral. We calculated the average count for each speaker and the average over all speakers for the complete game.

3. Results

3.1. Results of Study 1

We plotted the distribution of all the emotions detected by facial emotion recognition according to the above categories (Figure 3) for all the images. Clearly, the emotion most frequently detected was "neutrality". This was expected but nonetheless poses a limitation which will be discussed later. The emotion detected second was happiness, followed by sadness, anger, and surprise. Therefore, even if we see big differences between the detected emotions, the difference is still marginal compared to the percentage of neutrality measured in the participants' facial expressions.

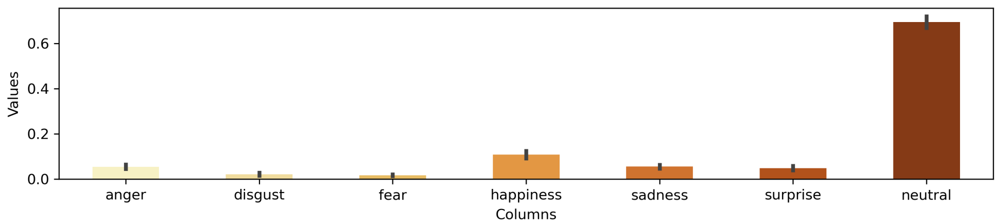

Figure 3. Distribution of the 7 detected emotions.

In particular, the emotions "fear" and "disgust" need to be interpreted with caution, as they were scarcely detected over the whole dataset.

Subsequently, each emotion was plotted independently to show the differences between image groups (Figure 4).

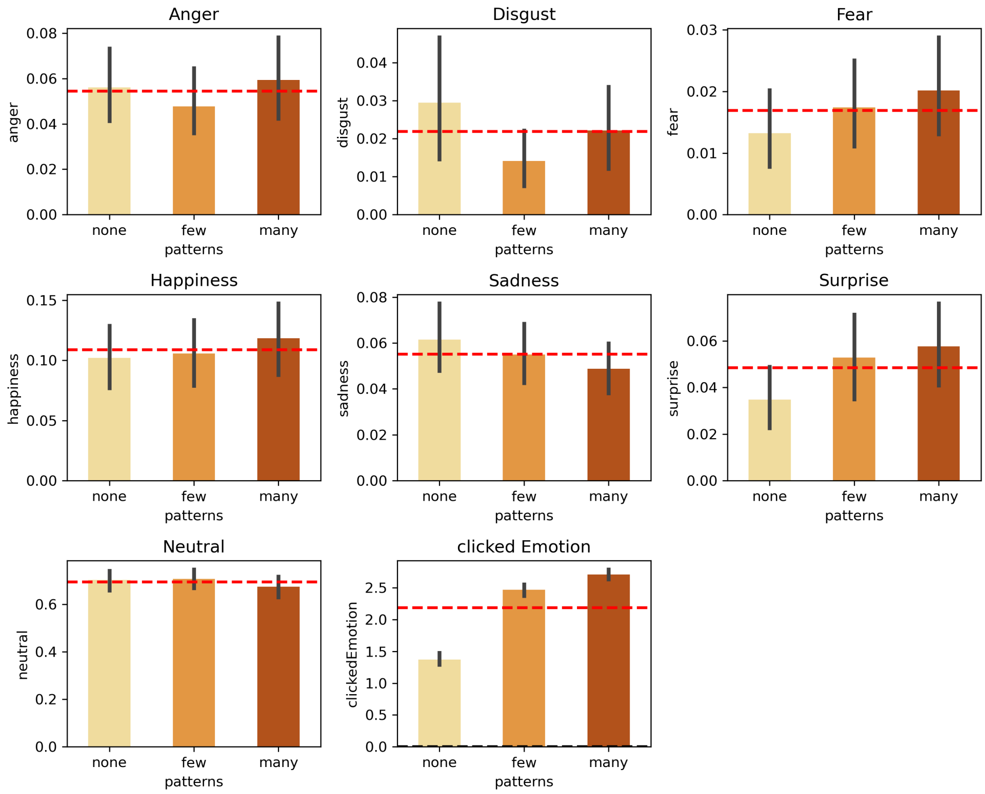

Figure 4. Differences for every emotion between image categories. The emotions labeled anger, disgust, fear, happiness, sadness, surprise, and neutral are automatically computed with FER, while each clicked emotion is chosen by the user in a survey (negative–neutral–positive). The red line shows the mean of each respective sentiment over all image categories.

First, the neutral category is shown to be the same for all groups, which is very helpful because it allows us to neglect the influence on emotions. Also, the relative strengths of the emotions according to the intensity groups can be divided into three different patterns as follows (note: the percentages are the deviations from the average across all groups):

(a) Emotions that become more intense when more biophilic characteristics are present. These are fear where participants showed an 18.9% increase, happiness with a 8.9% increase, surprise with a 19% increase, and the self-stated emotion being 24.1% more positive.

(b) The emotion sadness seems to be decreasing when more biophilic characteristics are present, decreasing by 11.4%.

(c) Anger (−12.3%) and disgust (−35.7%) seem to be at lowest when only a few biophilic characteristics are included in the images. Anger increases the most with 9.2% when many biophilic patterns are present and disgust has its highest with an increase of 34.2% when the architecture shown in the images had no aspects of biophilic design at all.

A comment is relevant at this point. Due to the statistically small population, the very high variances in the computed differences between the emotions in relation to the intensity of the three groups of biophilic design criteria limit the subsequent significance and correlation testing.

To make generalized assumptions and conclusions from these results we need to test each difference in emotion for significance. We did this for each sub-plot and between all three groups. First, we determined the distribution of our collected data. As the

Shapiro–Wilk test shows that our data was not normally distributed, we tested our data for significance applying the Wilcoxon signed-rank test with alpha = 0.05. In total there were six cases where we could not show a significant difference between the groups (Table 1). The first significant result is the difference between "disgust" detected between the ["few" and "many" biophilic qualities] image categories. The test for "fear" between the groups ["few" and "many"], and ["none" and "many"] both yielded p-values lower than our chosen level of significance. And, finally, the difference in the "clicked emotion" between the ["few" and "none"], ["few" and "many"], and ["none" and "many"] groups, respectively, proved to be significant in all three cases. As these are self-documented emotions, there is enough evidence in the complete data sample to form a general statement from these results.

Table 1. Emotions with significant differences between test groups using Wilcoxon signed-rank test.

Emotion	Compared Groups	*p*-Values
disgust	few vs. many	0.009
fear	few vs. many	0.003
fear	none vs. many	0.041
clicked emotion	few vs. none	~0
clicked emotion	few vs. many	0.0001
clicked emotion	none vs. many	~0

We additionally tested the relationship between emotions tracked with FER and the self-stated emotions (negative, neutral, and positive). The FER emotions happiness and surprise have a statistically significant increasing monotonic relationship, which means that participants tend to state that they felt more positive about the shown image when it had more biophilic elements. Furthermore, the FER emotion sadness has a decreasing monotonic relationship with the self-stated emotion, meaning that participants showed a sadder face when looking at pictures with fewer biophilic elements. This correlation helps to join conscious with unconscious subject responses to biophilic visual elements, which was one of our objectives.

To answer the research question more accurately and counteract the high variance, we decided to group the FER emotions into the same three groups as the self-stated emotions. As a basis we used the classification of GoEmotions suggested by Google Research in 2021 [46]. Anger, disgust, fear, and sadness are classified as negative, whereas happiness and surprise are classified as positive: neutral and the self-stated emotion remain independent groups. Even though surprise is classified as ambiguous in Google Research, we decided to include it in the positive group because, based on the previous analysis, we found an increasing relationship with the self-stated positive emotions.

With the grouping, we first repeated the significance analysis but only the self-stated emotion had a significant difference between the three levels of biophilic design (none, some, a lot). A correlation analysis shows that there is a significant increase in self-stated emotion when more biophilic design is present in a picture of a built environment. Repeating the correlation analysis for the grouped FER emotions (negative, neutral, and positive) shows a statistically significant decreasing monotonic relationship between self-stated and negative FER emotions, and a significant increasing monotonic relationship between self-stated and positive FER emotions.

3.2. Results of Study 2

The analysis begins by looking at the productivity differences. We bisected the analysis in the individual and in the group games, and compared both, to provide a comprehensive understanding of the factors that influence both individual and group productivity (Figure 5).

The differences in team engagement and sentiments between the outside and inside locations were then compared. Two parameters that provide insights in productivity are total game time and number of moves. In the individual games, the participants needed on average 106.3 s inside and 100.3 s outside to finish the game, which is a decrease of

5.64 percent. The relative number of moves is even closer, with 39.2 inside and 38.06 outside, which is a decrease of only 2.89 percent. The groups needed a little bit longer in general but with a more significant difference. The time to complete the game was 122.4 s on average inside and 103.2 s outside, which is a decrease of 15.68%. The number of moves in the group games differs by only 1.32 percent, with 30.4 on average inside and 30.8 outside. There is an improvement in outside playtime for both individual and group games. Additionally, while groups tend to need longer for games, they generally need fewer moves. In terms of the number of moves, there seems to be no difference between playing inside and outside.

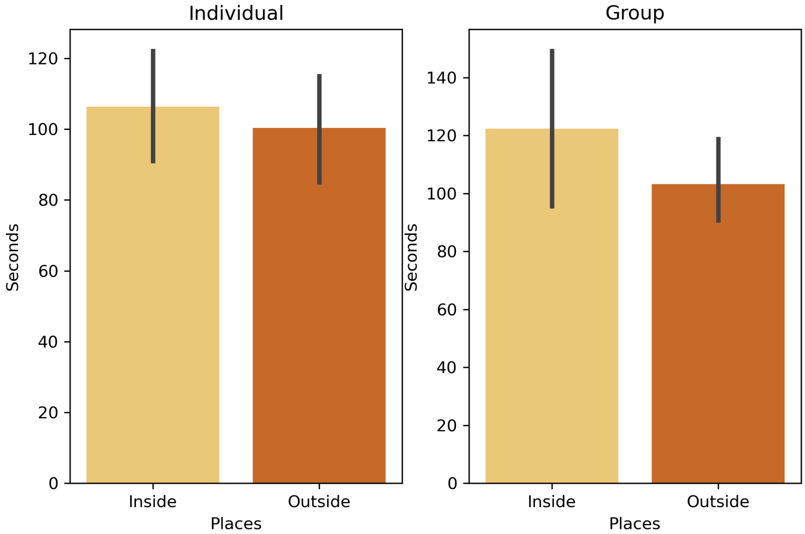

Figure 5. Change in productivity comparing inside and outside. Less time implies more efficient thinking. Black lines show range of the individual times.

Next, consider the sentiments and team engagement (Figure 6). The self-stated sentiment improves drastically by 13.88% for the outside location. This also applies to the detected positive sentiment, which improves by 7.51%, while the negative sentiment decreased by 8.46%. Separately, the measure of spoken words decreased by 12.33% from inside to outside. These data imply that the participants experienced a much better emotional state outside, as evidenced by both self-reported and audio-extracted emotional states. Interestingly, productivity also increased outside for the groups even though they talked less to each other.

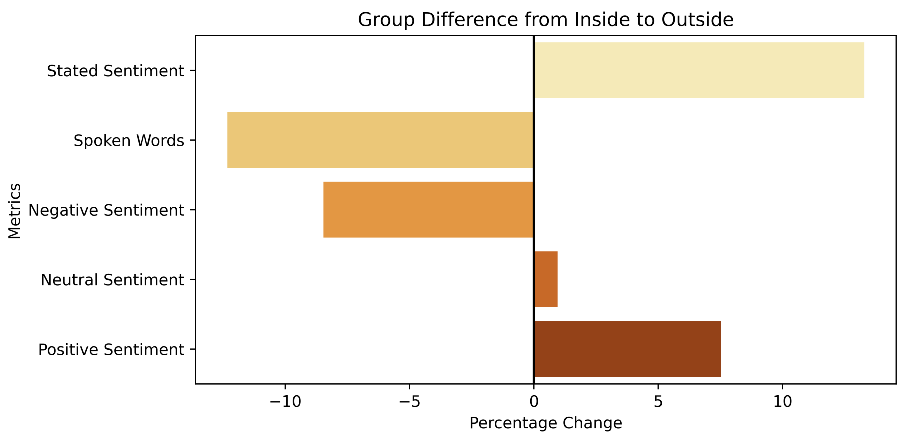

Figure 6. Change in team engagement and sentiment comparing inside to outside locations.

In alignment with the procedure outlined in Study 1, the Shapiro–Wilk test was used to unveil the underlying data distribution. As before, we used the Wilcoxon signed-rank test because it does not require normally distributed data. Testing for significance between inside and outside data of the different metrics shows that self-stated sentiment as well as positive sentiment both vary significantly.

4. Discussion

4.1. Review of the Experimental Results

These two pilot studies give promising first conclusions, illustrating that quantitative methods and AI can be used to measure the positive impact of biophilic design elements. Two complimentary experiments demonstrated the positive influence on emotions and cognition, revealing that biophilic design qualities lead to higher satisfaction and increased cognitive performance of the participants in each study.

Even considering the first study's limitations, we can answer the question "Does biophilic design in architecture trigger more positive emotions?" with YES, based on our analysis. We find a clear indication that the mere presence of more biophilic design characteristics in the built environment triggers more positive emotions.

The results met our assumptions and expectations. The study design was clear and we were able to obtain enough data to apply a comprehensive analysis. However, there were also some results—such as for the emotions "fear" and "surprise"—that showed an increase for pictures with more biophilic qualities and a decrease for pictures with fewer biophilic qualities. This result is interesting as "fear" is clearly a negative valence emotion. We researched a possible explanation for this observation.

As described in Section 2.1, biophilic design involves not only the addition of plants and water but also refers to the "nature of the space": geometrical qualities such as nested symmetries, colors, fractals, etc. [2–4]. Images that display some kind of peril like the New York Hearst Tower or the Sir Duncan Rice Library in Aberdeen would be expected to trigger a reaction of surprise more often than pictures of smooth, purely concrete facades. These might be reasons for the results that show a proportional increase in detected surprise for more biophilic design qualities found in a building.

A closer look at these two emotions ("fear" and "surprise") and the respective facial expressions reveals that they are in a sense related to each other [47]. Similarities might be manifested as wide-open eyes, raised eyebrows, and an open mouth. When taking this into consideration, the detected emotion of "fear" might as well be a falsely detected "surprise". The lack of detected emotions other than "neutral" made it important to interpret and assess results (such as these) carefully. This is the reason we decided not to rely too much on the results for "fear" and "disgust", as they were scarcely detected by our FER (facial emotion recognition), being the two least detected emotions overall.

Those two emotions aside, with the results of our data sample, consisting of reactions for 15 architectural structures by 39 people, we are clearly able to answer our research question: does biophilic design in architecture trigger more positive emotions? The results for "happiness" (positive), "sadness" and "disgust" (negative), and most of all "clicked emotions" show that biophilic design indeed fosters positive emotions, given that reducing negative emotions increases the presence of positive emotions.

The results of Study 1 confirm the overall findings by other researchers on the positive impact of biophilic design [2,6,35]. We assume that this result holds true for a much larger sample, based on the significant results of the clicked emotions. Here, we could even make out significant differences in the responses according to different numbers of biophilic qualities per picture and were not only distinguishing a complete lack versus an abundance of them.

Study 2 yielded similar results, by revisiting the research question: Can the presence of biophilic design elements in a work environment enhance productivity, team engagement, and overall sentiment?

A clear trend in both the individual and the group games is that the participants were faster, with the same number of moves. Through both self-assessment and sentiment analysis of the conversations that took place, the above research question is answered for the most part with YES. However, we also discovered that the participants used fewer words outside. Therefore, an unambiguous statement on whether the team engagement was better or worse is not possible. Although fewer words were used outside, the data show that the participants were better at the game.

As in the first study, we could clearly make out tendencies for the productivity metrics to decrease when being immersed in a natural setup (Figures 5 and 6). The time difference for game completion for groups when playing outside and inside was especially impressive, although this trend could not be observed in the individual cases. The difference in words used in each location might be explainable through a kind of flow state and this would be another indicator for improved productivity. However, none of these differences turned out to be significant outside of our data sample. The only thing we were able to show was the positive impact on the sentiment once again, but without any correlation between productivity and sentiment within our correlation analysis.

This might be a good point on which to start further research on this topic. The research question "Does the presence of nature improve productivity?" could be answered positively even when considering our small data sample. The obtained results apply on a limited level.

4.2. Proposing a Direction for New Experiments

It is useful to classify existing studies involving biophilia into three broad categories: (1) conscious user surveys, (2) using medical sensors to directly measure unconscious bodily reactions, and (3) indirect measurements that judge the state of the body and physical functions without the subject's awareness. The pilot studies reported here fall into this third category of investigation. Considering the relative ease and non-invasive nature of such studies, we hope to inspire other investigators to develop research in this direction. We express confidence that such projects will help to answer long-standing questions about the use of architectural spaces having distinct characteristics. This question is of fundamental importance to the industry.

As we already discussed in Section 3, a distinct goal of this pilot project is to draw attention to the possibilities of an indirect evaluation of biophilic environments. We suspect this approach to be more consistently accurate than the usual consciously performed survey, according to the following argument. Everyday settings combine natural with built elements and those contribute independently to the positive biophilic effect upon people who experience them. However, whereas almost everybody likes to have accessible natural green, individuals can have very different opinions about the architecture of particular settings. Such decisions are motivated by the visual style, including color, ornamentation, shape, surface texture, etc. Yet, both built and natural structures will contribute to the valence (positive, negative, or mixed) of people's unconscious reaction to them, a reaction that cannot be controlled.

Because of their education and media exposure, some users will "like" a particular architectural style that has few if any biophilic qualities, yet their body will respond in a consistent manner according to human physiology; in some cases opposite to their stated opinion [2–4]. For this reason, an unbiased assessment of the total biophilic properties using indirect measurements, as was carried out here, is able to sidestep subjective opinions arising from the architecture.

5. Limitations

For the first study presented here, a primary limitation surfaced in the form of insufficiently pronounced emotional facial expressions among the participants, as individuals may not necessarily alter their facial expressions triggered solely by observing diverse images. This result is hard to avoid without changing the entire framework of the study, for example by having a group of people visit architectural structures in real life. A direct, physical encounter would probably increase the detectable emotions through a shared, more immersive experience, but this study option exceeds our means. Furthermore, our test group proved to be very homogeneous socially, which makes it harder to draw generalized conclusions.

This limitation holds true even more for Study 2, as the increased effort of joining our study at real-life locations made it hard to get people to participate. Additionally, the chosen productivity and team engagement measures might need some reworking, as playing a game of memory does have a huge training effect. We tried to counter this possible bias by alternating each group's starting position (either inside or outside), but there might be better solutions. The memory game also did not animate the study subjects to communicate verbally as much as we expected that it would. In a time relevant game, sentences like "yes" or "no" are often used and the NLP (Natural-Language-Processing) model sees those as incomplete, hence detects them as negative. Therefore, another game choice might return better results here.

Despite certain limitations in this pilot project, we are optimistic that the results will serve as a source of inspiration for future research endeavors. With a better FER (facial emotion recognition) setup, or even a real-life application of Study 1, the outcome might prove to yield more generalizable and insightful results. Moreover, the number of images used could be expanded, making it possible to compare the effect of individual biophilic design qualities with one another. To quantify the positive relationship between biophilic qualities and positive emotions, one idea would be to create a large baseline repository correlating change in emotion with specific architectural qualities. Additionally while the study did not explicitly track participants' gender, efforts were made to maintain gender balance. We recognize that this is a crucial demographic variable that should be considered in future research endeavors.

For Study 2 future research could target the collection of more data from around 30–40 or more test subjects in order to produce significant results. It might also be worthwhile to test other productivity measurements instead of only using one task per location. Lastly, it is worth considering the possibility of expanding the range of locations; perhaps including locations that incorporate different numbers of biophilic design qualities.

6. Conclusions

This study has broad practical and theoretical implications. On the theoretical side it illustrates the wide applicability of biophilic design concepts for architecture and construction so as to increase human well-being. The biophilic framework gives researchers a tangible way to measure and quantify knowledge of how humans unconsciously react to their environment. On the practical side it shows architects the advantages of biophilic design, motivating its use in interacting with their constituency. Additionally, encouraging the use of biophilic concepts promotes the integration of nature into living spaces, which consequently improves the creation of more sustainable environments.

This pilot project conducted two separate studies to measure the impact of biophilic design on human beings in various ways. Most related work targets the well-being and health aspects related to this design approach, using both personal surveys and direct medical sensors. Our goal was to measure the emotions evoked through confronting biophilic design unconsciously, as well as the difference in productivity depending on one's immediate environment. Results from this study showed that biophilic design indeed enhanced positive emotions and productivity, thus supporting the overall consensus in this research domain of the positive and important impact of biophilic design.

The literature contains a considerable number of studies where subjects self-report on their actions and feelings when influenced by biophilic design, or while being situated in a natural biophilic environment. The two reported experiments deduced positive unconscious effects of a biophilic environment, which are measured indirectly using data that is processed by artificial intelligence. This aspect of the pilot study is novel and aims to encourage other groups of researchers to utilize the wide range of recent technological developments that make similar studies possible for the first time. For practitioners, our study reveals a new way of measuring the degree of positive impact that the integration of biophilic qualities will have on their architectural designs.

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Institutional Review Board Statement: The research study design conforms to the ethical norms and standards of the Declaration of Helsinki and was approved by University of Cologne.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: Authors Peter A. Gloor and Nikos A. Salingaros are affiliated with non-profit research lab (instituted as a Swiss Verein) Galaxylabs. All authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Appendix A

Table A1. Chosen images and their respective Biophilic Design Patterns.

Building	Biophilic Design Patterns
New York Grand Central Terminal	P8, P10, P11
New York Hearst Tower	P11, P14
Sir Duncan Rice Library, University of Aberdeen	P8, P10, P14
KU Leuven Central Library, Antwerp	P9, P10, P12
Royal Children's Hospital Melbourne	P1, P2, P10
Stockholm White Mountain Office (1)	P1, P2, P6, P9
Stockholm White Mountain Office (2)	P3, P6, P9, P13
Madrid Selgascano Architecture Office	P1, P6, P7, P12
UP Ipswich Library, University of Queensland, Brisbane	P1, P2, P7, P11
Community Hospital of the Monterey Peninsula	P1, P2, P3, P5, P7, P10, P13
Museu Nacional da Republica Brasilia	-
Cologne University Library	-
Hachioji Library, Tama Art University, Hachioji	-
Biblioteca Nacional de Brasilia	-
Jakarta Ogilvy Office	-

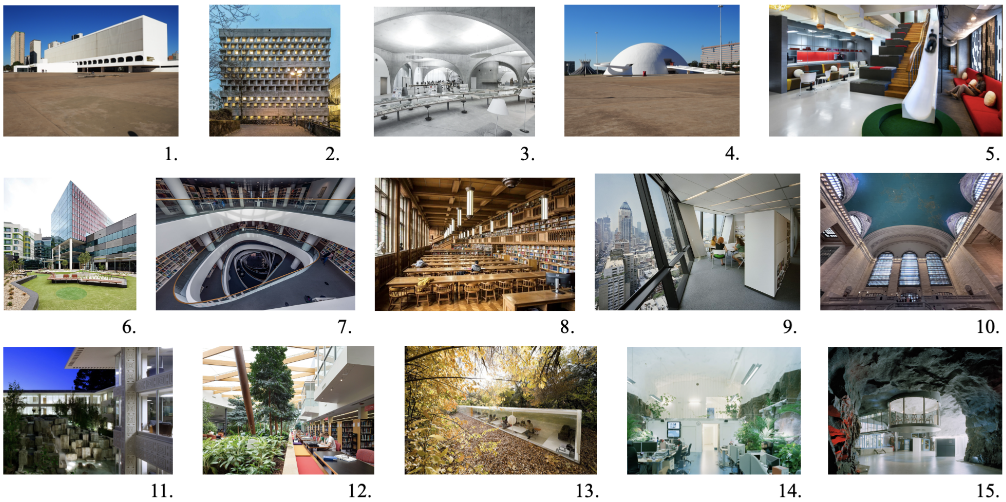

Figure A1. Images used in Study 1 | All websites were accessed on 1 September 2023 | 1. Biblioteca Nacional de Brasilia, photo by N.H. Buras, used with permission. 2. Cologne University Library, photo by Gregor Zoyzoyla, from sosbrutalism.org. 3. Hachioji Library, Tama Art University, Hachioji, photo by Rasmus Hjortshøj, used with permission. 4. Museu Nacional da Republica Brasilia, photo by N.H. Buras, used with permission. 5. Jakarta Ogily Office, from officesnapshots.com. 6. Royal Children's Hospital Melbourne, photo by ANLC and Street Furniture Australia, used with permission. 7. Sir Duncan Library, University of Aberdeen, photo by Jan Hoogendoorn, from Flickr.com. 8. KU Leuven Central Library, Antwerp, photo by Wentao Jiang, Wikimedia Commons. 9. New York Hearst Tower, from sections.arcelormittal.com. 10. New York Central Terminal, photo by N.H. Buras, used with permission. 11. Community Hospital of the Monterey Peninsula, photo by HOK Network, from pinterest.com. 12. UP Ipswich Library, University of Queensland, Brisbane, photo by Wilson Architects Australia, from wilsonarchitects.com.au. 13. Madrid Selgascano Architecture Office, photo by Roland Halbe, from archdaily.com. 14/15. Stockholm White Mountain Office, photos by Lindman: Photography, from archdaily.com.

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