Meta-Analysis

An Assessment of the Quantifiable Effects for Expressed Timber Biophilic Treatments: A Case for Mass Timber Construction?

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Biophilia refers to the innate human inclination to connect with nature. Mass Timber Construction (MTC) may hold the key to increasing the adoption of biophilic treatments in sustainable architecture through the inherent properties of timber. Existing literature on biophilia has explored its benefits and adoption strategies, however, these studies predominantly emphasise the short-term effects on human health and well-being relying on subjective measures. There exists a research gap in comprehending the long-term and sustained benefits of biophilic environments from a more comprehensive perspective that considers both subjective and objective measures. Utilising the Meta-Essentials tool, the present paper aimed to conduct a meta-analytic review of the literature examining both subjective and objective outcomes from biophilic experimentation not previously examined seeking support for MTC and its potential biophilic effects. A total of 11 studies were considered part of the final review with a combined sample size of 727 participants. The main findings included an overall moderate effect for participants subjected to biophilic environments, including exposure to wood interior treatments. A sub-group analysis of subjective and objective measures also indicated a mild effect in each domain. The findings support previous meta-analysis evidence for the utility of biophilic design and application to internal environments. The outcomes of quantifying biophilic health benefits are crucial for the development of mass timber-constructed buildings for several reasons. Firstly, it can help justify the use of wood and mass timber as sustainable alternatives to traditional building materials, such as concrete and steel, by providing evidence of their positive impact on human health and wellbeing. Secondly, it can inform the design process, enabling architects and designers to create spaces that maximise the biophilic response and optimize occupants' health and wellbeing outcomes. Lastly, it can contribute to the broader goals of sustainable architecture by demonstrating the potential of biophilic design in achieving sustainability targets, such as enhancing productivity, biodiversity, and circularity.

Keywords: *biophilic, mass timber, quantification, meta-analysis, health benefits*

Introduction

Proclaimed as one of the key benefits of the adoption of Mass Timber Construction (MTC) is the biophilic health effects derived from exposed timber within buildings. The concept of biophilia refers to the innate human tendency to seek connections with nature and has gained significant attention in the fields of architecture, design, and environmental psychology (Gunnarsson & Heblom, 2023). MTC is a primarily structural system in a building however it is also gaining popularity as an interior aesthetic solution through the expression of timber used in the columns, beams, soffits, and interior walls/floors. There is a scarcity of evidence in the literature to support these claims and an absence of evidence for the biophilic effects beyond subjective perceptions, for example how someone feels occupying a biophilic treated environment. Therefore, the present paper aimed to conduct a meta-analytic review of the literature examining both subjective and objective outcomes from biophilic experimentation seeking support for MTC and its potential biophilic effects. In what follows next is an overview of biophilic design, a brief review of environmental psychology and architecture, several brief case studies regarding MTC projects, a review of the variables commonly assessed in biophilic experimentation and the meta-analytic review itself looking for evidence in support of a case for MTC and biophilic effects from timber.

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Biophilic Design

Biophilic design aims to incorporate natural elements and features into the built environment to enhance the well-being and health of occupants (Figure 1).

Figure 1. Artist rendering courtesy of Next Property Group, Fiera Properties, and BNC Inc. Architecture + Urban Design)

The importance of biophilia lies in its potential to positively impact human health and create sustainable and restorative environments (Barbiero & Berto, 2021; Ulrich, 1984). Grinde & Patil, (2009) and Yin et al. (2020) highlight the benefits of biophilic treatments on human health conditions within architecture. Exposure to nature and natural elements has been associated with reduced stress levels, improved cognitive function, attention restoration, and focus, and enhanced psychological well-being (Grinde & Patil, 2009; Yin et al, 2020). For example, it has been suggested that visual contact with nature (Figure 2), such as having a view of green spaces or incorporating indoor plants can have a positive influence on individuals' health and wellbeing. It has been suggested that biophilic exposure is associated with physiological aspects of human well-being including lower blood pressure, and heart rate as well as psychological factors, including improved mood, and increased subjective well-being satisfaction leading to enhanced productivity in the workplace (Putrino et al., 2020) expand this literature on how they suggested those health-related results.

Figure 2. Render by Proscenium Architects | Photo: KK Law Source: www.thinkwood.com

While some short-term effects of biophilia on human health and well-being have been well-documented, these are mainly found to be based on subjective measures and as such there is a research gap when it comes to understanding the long-term effects and sustained benefits of biophilic environments (Barbiero & Berto, 2021). Indeed, Barbiero and Berto (2021) focused on immediate physiological and psychological responses to biophilic elements, such as natural mass timber surfaces, greenery, and access to natural light. To fully understand the potential long-term effects, it is crucial to investigate the sustained benefits individuals experience from biophilic environments over extended periods.

Exploring the incorporation of biophilic elements in workplaces, apartments, schools, and other building typologies can provide valuable insights into the long-term impacts on occupant well-being, health outcomes, and productivity. Additionally, the COVID-19 pandemic has highlighted the significance of assessing the post-pandemic health and well-being of occupants in biophilic environments (Cacique & Ou, 2022). Understanding the impact of biophilic design on occupant well-being, especially in the context of post-occupancy use of the building and behaviour (Engelen et al., 2022), can provide valuable insights into the effectiveness of biophilic interventions in mitigating the negative effects of the pandemic (Barbiero & Berto, 2021).

The Origins of Environmental Psychology and Architecture

Environmental and architectural psychology offer insights into the human relationship with wood, focusing on how individuals interact with their surrounding environments. These fields also delve into human preferences for varying settings. Initial investigations in environmental psychology concentrated on the adverse impacts of surroundings on individuals (Gärling and Golledge, 1989). Ittelson (1960) explored the influence of institutional design on individuals with mental health conditions, coining the term "environmental psychology." A significant portion of this research strand centred on the detrimental effects of congestion, noise, and pollution (Gärling, 2001; Gärling et al., 2002), leading to the emergence of architectural psychology, which aims to mitigate such negative consequences through design.

Research into people's selection of environments spurred notable advancements in identifying positive settings. Throughout this quest for positive environments, nature consistently emerges as a prevalent theme. Drawing from studies on aesthetic preferences, Wohlwill (1968) postulated that natural scenes featuring moderate visual complexity would be most favoured. However, this hypothesis failed to fully elucidate scene preferences why? It would be good to expand and explain how. Kaplan et al. (1972) introduced scene content as an additional factor, comparing natural and urban scenes. Their findings indicated that while complexity couldn't predict preference, content could.

The recurring preference for nature in the literature prompted researchers to explore its underlying causes. Balling and Falk (1982) suggested an inherent or evolutionary inclination towards natural scenes. Kaplan (1987) proposed that such a preference would evolve or be acquired if natural scenes provide advantages or benefits. These advantages remain relevant even in modern times. Ulrich (1984) discovered that patients recuperating from similar surgeries exhibited differing recovery rates and pain medication requirements based on their room views. Patients with views of a park experienced faster recovery and required less pain medication compared to those with a view of a building. Vederber (1986) offered similar evidence and shifted the focus back to the impact of environments on individuals, with an emphasis on the positive effects environments can yield.

Kaplan and Kaplan (1989) coined the term "restorative environments" to describe positive settings whereby studies and theories under this philosophy predominantly revolve around attentional fatigue and its alleviation through immersion in natural surroundings.

Ulrich (1991) introduced a parallel theory of restorative environments, positing that natural settings hold greater potential for psychophysiological stress recovery. Natural settings seem to provide restorative effects for humans (Kaplan and Kaplan, 1989). Moreover, individuals appear to recognise that natural environments are more rejuvenating (Herzog et al., 2002), and they exhibit a preference for such environments.

Lohr et al. (1996) took the innovative step of introducing natural

elements into indoor environments. They investigated the impacts of plants on task performance and stress levels indoors. Lohr et al. (1996) examined the effects of plants in indoor environments, specifically on pain perception.

Their findings revealed that subjects in rooms with plants exhibited higher pain thresholds compared to those in plant-free rooms. Shibata and Suzuki (2002) delved into the effects of plants on task performance, determining that the presence of plants improved creative task performance. These studies are significant for their integration of natural elements into built environments.

Mass Timber Construction and Biophilic Treatments

The adoption of MTC as a sustainable construction solution for the superstructure has also given rise to the use of the structure as an aesthetic interior treatment. The following brief case studies exemplify how mass timber is currently utilised to maximise its biophilic treatment effects.

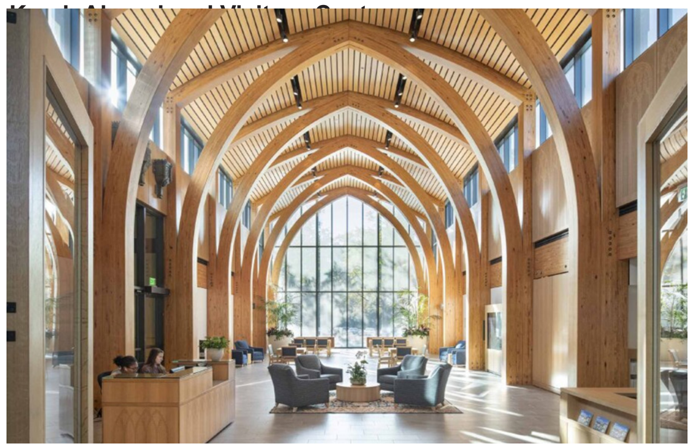

Figure 3. The Karsh Alumni and Visitors Centre (Photography by Peter Aaron; The Architects Newspaper, 2021).

Architect: Centerbrook Architects
Location: Durham, North Carolina
Landscape Architect: Stephen Stimson Associates Landscape Architects
Structural Engineer: LHC Structural Engineers
MEP/FP Engineer: Dewberry
Civil Engineer: HDR
Contractor: LeChase Construction Services
Lighting Design: Cline Bettridge Bernstein Lighting Design

The Karsh Alumni and Visitor Centre is part of the Duke University campus infrastructure and exemplifies the universities identity and a "university in the forest". The mass timber superstructure is formed by GluLam arches as a representation of trees, the expressed wood panelling encloses the space, and natural light fills the void with a outlook to the trees in the grounds surround the building.

EF Education First

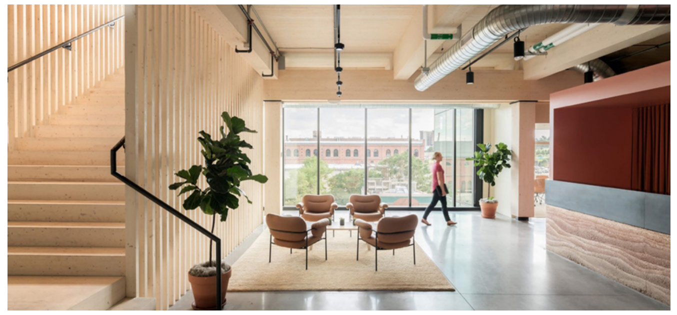

Figure 4. EWF Education First (Photography by David Lauer; The Architects Newspaper, 2021)

Designer: Gensler
Location: Denver
Acoustical Consultant: K2 Audio
Client and Collaborator: EF Architecture & Design Studio
General Contractor: Rand Construction
MEP Engineer: Salas O'Brien
Structural Engineer: KL&A
CLT/TimberSupplier: Nordic Structures

The EF Education First building has a mass timber superstructure comprised of Cross Laminated Timber (CLT) and various timber interior finishes, and the design takes inspiration from the natural beauty of Colorado's red rock canyons, with the expressed timber paneling evoking a feeling like hiking through the forest. The space has large windows allowing natural light to enter the space and reflect off the naturally expressed surface finishes.

Kendeda Building for Innovative Sustainable Design

Figure 5. Kendeda Building for Innovative Sustainable Design (Photography by David Lauer; The Architects Newspaper, 2021)

Design Architect: The Miller Hull Partnership
Collaborating Architect and Prime Architect: Lord Aeck Sargent
Location: Atlanta
Timber Installer/Framer: Universal Timber Structures
Timber Supplier: Unadilla Laminated Products
Salvaged Lumber Finishes Supplier: Raydeo Enterprises
General Contractor: Skanska cite
Landscape Architect: Andropogon
Design Engineer: PAE
Electrical Egineer: Newcomb & Boyd
Civil Engineer: Long Engineering
Structural Engineer: Uzun + Case
Graywater Systems Water Consultant: Biohabitats

The Kendeda Building achieved the Living Building certification, a high-standard sustainability award, for the use of timber and a hybrid on materials. The building includes a mass timber superstructure with expressed GluLam columns and beams, the use of timber in the stairs and walkways contrasts the polished concrete, and the soffit uses timber battens to complete the enclosure of the spaces. The building has substantial natural day light through large windows where occupants can view the landscape.

The three case studies presented here represent a transformation in the blurring of the boundaries between the structural elements of a building using MTC and the interior finishes that represent a biophilic design philosophy. The sophistication of the biophilic treatments currently applied to MTC is on the ascendancy. Whilst the interiors are aesthetically pleasing a question remains as to the actual health benefits derived from inhabiting or occupying these spaces.

Quantifying Biophilia and Health Benefits

Biophilic design incorporates elements and features from the natural environment into built spaces to create a connection with nature (Gunnarsson & Heblom, 2023). Numerous studies have investigated the physiological and psychological responses associated with exposure to biophilic elements and having a significant impact on reducing stress and anxiety levels. The following is a short selection for example purposes.

A study by Tsunetsugu et al., (2005) demonstrated that a room adorned with 45% coverage of timber material elicits an enhanced sense of comfort, manifesting in a noteworthy reduction in diastolic blood pressure and considerable increases in pulse rate (see Figure 3.).

Conversely, heightened wood coverage (90%) has been associated with a decline in brain activity, a phenomenon that can prove advantageous in settings that prioritise restoration, such as spas or medical facilities, or detrimental in spaces where a high level of cognitive functionality is anticipated (Tsunetsugu et al., 2005).

A further study by Fell (2010) employed a psychophysiological approach to examine stress, focusing on the autonomic nervous system's sympathetic and parasympathetic branches. The research involved four office settings: wood with plants, wood without plants, no wood with plants, and no wood or plants. A total of 119 university undergraduate students were allocated to these conditions. The Fell (2010) experiment included a 10-minute baseline reading and a 12–20-minute stress-inducing task. Followed by a 10-minute recovery phase. Skin conductance and IBI were continuously monitored.

Results indicated that exposure to wood affected sympathetic system activation, as demonstrated by lower skin conductance levels (SCL) and reduced frequency of non-specific skin conductance responses (F-NS-SCR) during baseline and throughout the study. No similar effect was observed for plants concerning sympathetic activation, and no interactions between wood and plants were noted. Parasympathetic activation was measured using spectral analysis of heart rate variability (HRV) data, but no treatment effects on parasympathetic activation were identified.

In a study conducted by Yin et al. (2020) using Virtual Reality (VR) or Immersive Virtual Environment (IVE) technology, participants were 100 adults recruited via the Harvard Decision Science Lab (HDSL, a university-wide research facility for behavioural research) and exposed to different types of biophilic indoor environments (see Figure 4). The participant's levels of anxiety levels were measured by using the short version of the State-Trait Anxiety Inventory Test (Spielberger et al., 1983). The findings indicated that biophilic environments had a larger restorative impact than non-biophilic environments, leading to reduced stress and anxiety levels (Yin et al, 2020) this is a very good study to expand a bit more. These results suggest that incorporating "natural elements" into indoor environments can have a positive influence on individuals' physiological and psychological well-being.

Moreover, visual contact with nature has been found to play a crucial role in improving health and well-being. A review of empirical studies concluded that an environment devoid of nature may have negative effects on health and quality of life. Adding elements of nature, such as plants and creating parks or offering

Figure 3. Interior room designs (Tsunetsugu et al., 2005)

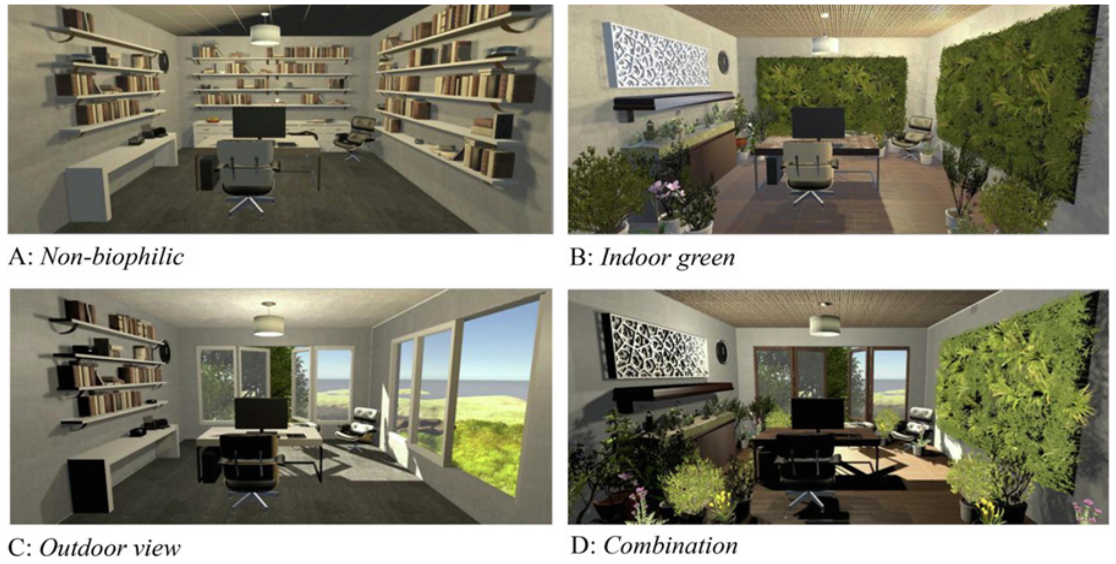

Figure 4. Four virtual reality office layouts in the Yin et al (2020) study

views through windows, can ameliorate these effects (Grinde and Patil, 2009). The presence of biophilic elements can help create a visually stimulating and calming environment, promoting relaxation, and reducing stress.

Constructs and Variables

Biophilic Interaction

Biophilic interaction refers to the various ways in which humans engage with nature and natural elements and the interaction occurs at different levels: indirect, incidental, and intentional. Indirect interaction involves non-physical engagement with nature, such as through visual stimuli. Incidental interaction happens spontaneously because of other activities, where people encounter nature unexpectedly. Intentional interaction is a conscious and direct effort to engage with nature, seeking a deliberate connection (Abdelaal, 2019).

Several patterns and features characterise biophilic interaction. First, viewing natural stimuli is a common way people engage with nature, whether it's looking at landscapes, plants, or animals. Additionally, humans interact with nature through their other senses, including auditory (sounds of nature), haptic (touch), olfactory (smells), and gustatory (tastes) stimuli. Non-rhythmic sensory stimuli, like the unpredictable rustling of leaves, also play a role in this interaction. Amongst others. the presence of natural elements can affect thermal comfort, ventilation, and kinetic systems, providing a tactile connection to the environment (Thomas and Xing, 2021).

Water features are another significant stimulus for biophilic interaction, offering soothing sights and sounds. Natural light and shadow patterns, created by sunlight filtering through leaves or reflecting on water, contribute to the sensory experience (Abdelaal, 2019). In many of the studies reviewed in the present paper, the use of indirect (non-physical, virtual environments, or through a window) exposure methods were used, and the level

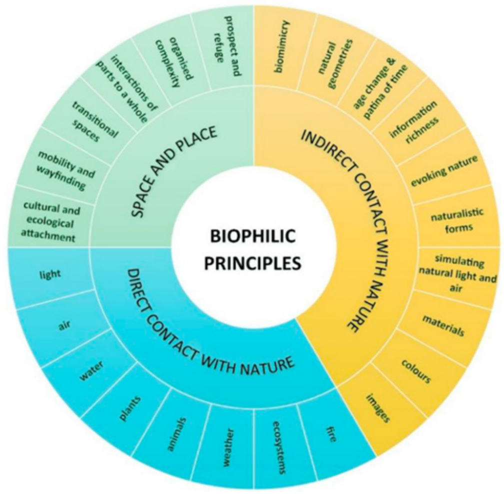

Figure 5. Biophilic design framework. (Thomas and Xing, 2021)

of interaction was based on natural light, natural stimulus, i.e., expressed timber or wood, and other sensory elements, such as colour used in interior or visual design interfaces. The following are the various constructs and variables used in studies to quantify the biophilic impacts on people.

1. Health and Wellbeing

The impact of nature on health and well-being spans various domains, as a review of the following articles details. Physically and physiologically, engaging with nature has been shown to reduce stress, positively influence the sympathetic nervous system (Lee & Lee, 2014), lower stress hormones (Li et al., 2008), decrease blood pressure (Alvarsson et al., 2010), alleviate headaches (Hansmann et al., 2007), and lead to perceived improvements in health (Chang et al., 2016). There's evidence suggesting a reduced occurrence of illnesses linked to natural exposure (Bringslimark et al., 2007). Psychologically, interacting with nature is linked to heightened self-esteem (Pretty et al., 2005), improved mood (Pretty, 2004; Pretty et al., 2005; Shibata & Suzuki, 2002), diminished anger and frustration (Kuo & Sullivan, 2001), enhanced psychological well-being (Kaplan, 2001), reduced anxiety (Wang et al., 2016), positive attitudes, increased happiness, and improved emotional responses (Windhager et al., 2011).

Cognitively, nature interaction promotes attention restoration (Jeon et al., 2018), diminishes mental fatigue (Moore et al., 2006), enhances academic performance (Fjeld et al., 1998), provides learning opportunities, improves task performance and cognitive abilities (Han, 2010), boosts productivity, increases mental engagement and attentiveness (Biederman & Vessel, 2006), aids in concentration and memory (Greenleaf et al., 2013), and fosters inspiration (Fredrickson & Anderson, 1999). On the social and spiritual fronts, nature facilitates social interaction (Kingsley & Townsend, 2006), empowers individuals socially (Zelenski & Nisbet, 2012), encourages interracial engagement (Shinew et al., 2004), bolsters social cohesion and support (Kingsley & Townsend, 2006), and contributes to spiritual well-being. Connecting with nature yields an array of benefits for physical health, psychological states, cognitive function, and social and spiritual dimensions of well-being. These positive outcomes encompass stress reduction, improved mood, enhanced cognitive performance, and a stronger sense of community and spirituality, all of which underline the importance of incorporating nature into our lives for holistic well-being. In what follows are a few select examples of objective and subjective measures used in biophilic experimentations employed as part of the studies reviewed in the present study.

2. Electrodermal

Electrodermal Activity (EDA) is regulated by the sympathetic nervous system, as explained by Dawson et al. (2007) in the Handbook of Psychophysiology. The sympathetic nervous system's involvement prompts eccrine glands in the skin to release sweat, subsequently reducing the skin's electrical resistance. The common method for evaluating EDA, is achieved by applying a constant voltage across electrodes on the hands or fingers and tracking alterations in electrical current. Activation of the sympathetic nervous system triggers the well-known "fight, flight, or freeze" response during stressful situations. A direct indicator of sympathetic activation is skin conductivity. When an individual experiences stress, the sympathetic nervous system stimulates sweat secretion in the eccrine glands, heightening skin conductivity. Various skin conductance parameters exist to assess the sympathetic reactions linked to stress.

3. Skin Conductance Response

Skin Conductance Responses (SCR) are transient surges in skin conductivity, indicating changes in arousal or stress levels. These responses can either be event-related - linked to specific stimuli like a loud noise - or non-specific - arising without a distinct trigger. Non-Specific Skin Responses (NS-SCR) are prompted by thoughts or cognitive processes (Nikula, 1991; Wise et al., 2011). A heightened frequency of NS-SCRs per minute corresponds to elevated stress levels (Dawson et al., 2007). The amplitude of SCR serves as an indicator of an individual's stress level. A larger amplitude signifies greater stress.

4. Cardiovascular

The measurement of the heart rate, specifically the InterBeat Interval (IBI) is an excellent indicator of the measures of sympathetic and parasympathetic activity in the body. To separate the parasympathetic component, an analysis called the Heart Rate Variability (HRV) is based on an additional analysis of the IBI. The IBI is a measure of the time between the spikes in the Electrocardiogram ECG waveforms. The HRV is a measure of the uniformity of the waves on the ECG, and IBI is shorter on inhalation and longer on exhalation, thus these components of 'breathing' can be broken into time and frequency-based assessments.

5. Attention and Responsiveness Measures

Attention can be measured in many ways. Common tests for attention include the Wisconsin Card Sort Test (WCST), the Tests of Variable Attention (TOVA), and the Necker Cube. The measure of attention is a factor for consideration in environments where attention is more conducive or less conducive. The measures are typically assigned in a pre-test and post-intervention assessment, or comparisons between groups, such as in a control room compared to one with biophilic treatment.

6. Subjective Satisfaction, Productivity, and Wellness Measures

The subjective measures within this category include Environmental Satisfaction measures, subjective emotion, and well-being scales which can provide subjective responses to accompany physiological objective measures to ascertain differences between people occupying different environments.

The present paper aimed to conduct a meta-analytic review of the literature examining both subjective and objective outcomes from biophilic experimentation seeking support for MTC and its potential biophilic effects. By synthesising and evaluating a select range of scholarly articles, this review aims to consolidate the current understanding of measures used (subjective and objective – physiological and psychological) in determining an approach to assessing the application of mass timber and maximise the benefits from biophilic design treatments. To this end, this study employs a meta-analytic approach, encompassing search, coding, and statistical procedures, to amalgamate the outcomes of previously published studies, specifically their variables that have produced an effect related to biophilic health benefits in built environments.

Methodology

1. Previous Meta-Analysis Review

A review of previous meta-analysis (Capaldi et al., 2014; McMahan and Estes, 2015; Gaekwad et.al, 2022; Jason et al., 2022; Gaekwad et al., 2023) exploring the biophilic effect was conducted ensuring that no existing meta-analyses cover the precise topic - to prevent redundancy of research efforts. Each of the identified previous studies exclusively focused on the field of

psychology exploring the effects of subjective measures, i.e., the Positive and Negative Affect Scale (PANAS; Watson et al., 1988) the ZIPERS (Zuckerman, 1977) and the Profile of Mood States (POMS) (McNair et al., 1971). Each study concluded support for an overall biophilic effect. None of the studies examined the composite of subjective and objective variables. The aim of this meta-analysis paper is to gain a comprehensive understanding of the long-term and sustained benefits of biophilic environments from a holistic perspective that considers both subjective and objective viewpoints. To the best of the authors' knowledge, no prior meta-analysis has been undertaken to evaluate these variables in such a manner.

2. Research Design

Effect size is a statistical measure used in research to quantify the magnitude or strength of a relationship or the size of an observed effect in a study. It provides a standardised way to express the practical significance or meaningfulness of a finding, independent of the sample size. A meta-analytic review involves the scrutiny of multiple analyses - a statistical examination of a substantial assemblage of outcomes drawn from individual studies, intending to amalgamate these findings (Glass 1976). It offers a meticulous and systematic evaluation that stands in stark contrast to the informal, narrative discourse commonly employed in some of the existing papers to comprehend the swiftly proliferating research landscape (Glass 1976). Meta-analysis, like any research approach, faces critique and opposition. Glass et al. (1981) delineated four central challenges, including mixing diverse measurement methods, combining 'poor' and 'good' studies, bias towards significant findings, and the potential for misleading reliability arising from segmented study portions. A strategic countermeasure involves pre-emptively addressing these issues in research design and execution (Wolf 1986). Thus, in the present study, disparate study factors/measures are evaluated, subgroup analysis is conducted to assess differences in subjective and objective measures, and biases in findings are scrutinised. The following sections provide details about each phase of the meta-analytic approach adopted.

3. Search Procedures

The following search strings and Boolean operators have been adopted to search for the articles. An example is provided here.

'biophilic design' AND/OR 'internal environments' AND 'experiments' AND 'sustainability' AND 'objective measures' AND 'subjective measures' AND 'well-being' OR 'wellness' AND 'statistical analysis' AND "experiments" OR "experimental design" AND "mass timber construction"

Following the development of the search term strings, the search was conducted using the RMIT reference library searcher system and Google Scholar reference to find relevant papers. The utilisation of the RMIT research engine offers the benefit of encompassing diverse databases including Scopus and ScienceDirect reference. Furthermore, Google Scholar has been employed as a source for articles. Unlike other databases, Google Scholar doesn't provide a list of publishers, journals, types of journals, or information about the timeline or refereed status of records. Nevertheless, leveraging Google Scholar's advanced search engine proves advantageous in capturing citations not covered by other databases (Bergman, 2012). After employing the search term strings in the RMIT library and Google Scholar, an aggregate of 70 research records have been identified.

Inclusion and Exclusion Criteria

Each study underwent a meticulous evaluation process, guided by stringent inclusion and exclusion criteria, to facilitate cohesive aggregation. The inclusion criteria consisted of studies that were published between 2000-2023, or PhD thesis/es, peer-reviewed articles including an experiment in which the design included the built environment, i.e., office locations, school settings, and virtual reality. The studies must have a detailed description of the biophilic treatments and the measures (objective and subjective) looking at the comparison groups.

Studies that did not meet the criteria of being peer-reviewed, composed in English, or aligned with the domain of interest were intentionally omitted from the review. The exclusion criteria included studies conducted using a clinical population or within a hospital setting, did not provide sufficient descriptions of participants, design, and analysis, or used quasi-experimentation techniques, and did not focus on health and well-being outcomes. The accounting of the papers reviewed within the present study is found in Figure 6.

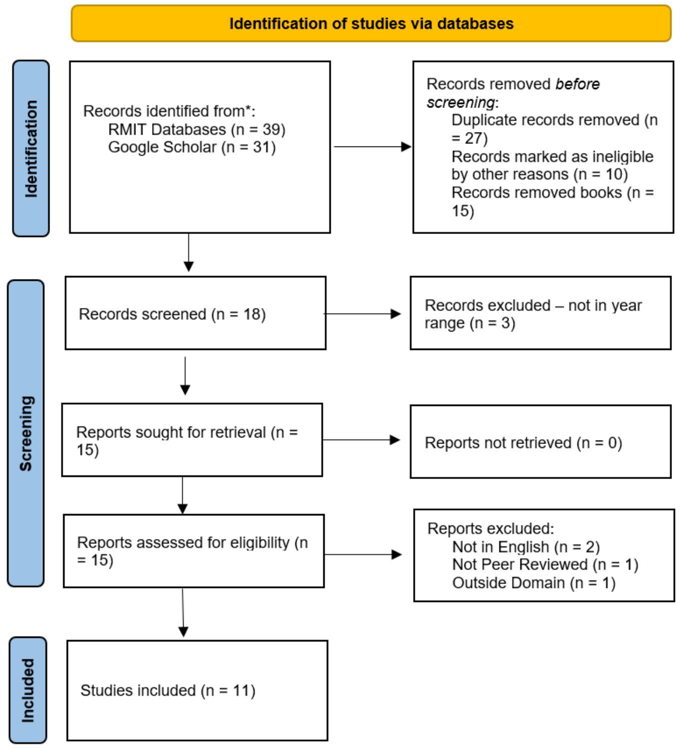

Figure 6. Accounting for the studies that were included in the final analysis.

The rigorous initial curation yielded a total of 18 papers. Subsequently, each paper's abstract underwent a scrupulous assessment by the primary author, aimed at discerning its alignment with the comprehensive scope of the present review. Through this thorough procedure, a refined selection process emerged, with an additional number of papers being excluded and ultimately culminating in the identification of a robust selection of 11 papers that are poised to contribute substantively to this meta-analysis.

Data Analysis Procedure

Reviewed papers were analysed to determine the nature of the studies. In all cases the studies measured factors derived from experiments in which participants were randomly assigned to either a control condition with no biophilic treatment of the room or an experimental condition including biophilic treatment. The degree to which the biophilic treatment was applied and the nature of the experiment are in Table 1.

All papers that formed a part of the review process were placed into a table and each was scrutinised for subjective and objective measures, the design, participants' statistically significant results from the experiments. The results of the statistical analysis (Analysis of Variance (ANOVA), t-tests (mean differences), and correlation) were all recorded and labeled by the factor and then assigned a sub-domain category, i.e., Subjective Productivity.

The use of statistical techniques such as Cohen's d and Hedges' g was calculated from the means, standard deviations, and the pooled deviation for all statistically significant subjective and objective measures to calculate the effect size using Cohen's d and Hedges' g, as the two main calculations. The calculation for Cohen's d.

$$\text{Cohen's } d = (M_2 - M_1) / SD_{\text{pooled}}$$

and,

$$SD_{\text{pooled}} = \sqrt{((SD_1^2 + SD_2^2) / 2)}$$

Where,

M = Mean of to data set for group 1 or 2 (M_1, or M_2)

SD_{pooled} = The pooled Standard Deviation from the two groups

Interpreting effect sizes involves a certain level of judgment in practice. Cohen (1988) provides the following benchmarks for effect size d: 0.2 for a small effect, 0.5 for a medium effect, and 0.8 for a large effect. However, it's important to acknowledge that Cohen (1988) also acknowledges in the same section that these descriptive terms of "small," "medium," and "large" are "relative, not only to each other, but to the field of behavioural science as a whole, and more specifically, to the particular subject matter and research methodology employed in each individual study" (Cohen, 1988, p. 25).

Statistical data analysis

Meta-Essentials (Suurmond et al., 2016) meta-analysis Excel (Microsoft, 2023) spreadsheet workbook was used for the analysis. The purpose of the workbooks is to facilitate the integration of various studies to undertake an overall analysis of the findings and to achieve an overall statistical value for the information gathered. The present study adopted a different use, whereby we analysed the various measures/factors which provide a statistical effect rather than the normal convention of a single measure as is usual convention. Thus, we have not looked at the study level, but rather at the variable level. Therefore, a single study can provide multiple effect size measures.

The primary output from a meta-analytic analysis is the Forest Plot. The Forest Plot represents the individual measurement outcome estimates in the form of a point and a (95%) confidence interval graphic representation. The Forest Plot provides an estimate of an interval in which the "true" effect (in the population) will most probably lie (Hak, et al. 2016, p. 6). In the Forest Plot, a smaller or larger bullet symbolises the point estimate, with the varying bullet sizes indicating the degree of influence a particular study has on the overall meta-analytic outcome (Hak et al., 2016).

Review of Papers and Results

A total of 11 papers were included in the final analysis, a summary of the papers is in Table 1.

Results

Preliminary Analysis

Effect size calculations consisted of results in which the polarity was oriented towards the desired outcome, for example, in the case of reduced physiological outcomes the expected polarity for a significant effect is negatively oriented. Conversely, participants might have increased subjective well-being (positive polarity). Given the present study employed a 'variable level review' all measures were positively oriented, through the application of a -1 conversion for all negative effect size calculations.

Overall Model

The effect sizes range was 0.19 to 1.07, indicative of varying degrees of impact. Analysis focusing on the fixed effects at 95% Confidence Interval, using Cohen's d the combined overall effect was 0.58, [*CI* = 0.47, 0.68], which according to Cohen (1988) is a moderate total effect. The overall model achieved a *Z* score of 11.14, *p* = <0.01. The overall model Forest Plot is found in Figure 7.

Heterogeneity

Given that the overall design was at the variable level, not the individual paper level, it is not surprising that the heterogeneity test for the overall model was not met, Cochran's Q = 25.05, I^2 = 23.24%, τ = 0.13 (τ^2 =0.02). By design, several studies produced various effects from numerous measures, as detailed in Figure 7. Where, Cochran's Q is a test of heterogeneity, and its significance indicates whether there is statistically significant variability among the effect sizes of the included studies. τ^2 represents the amount of true variation in effect sizes between studies. Higher values of τ^2 indicate more heterogeneity between studies. I^2 quantifies the proportion of total variability in effect sizes that is due to heterogeneity rather than chance.

Sub-group Classification Models

The subgroup effect sizes were categorised as objective and subjective measures Figure 8 provides the sub-group Forest Plot.

Objective Measures

The objective measures effect sizes range was 0.31 to 1.07. The category included reaction time differences, Alpha and Beta waves, and Skin Conductance Level tests. Analysis focusing on the fixed effects at 95% Confidence Interval, using Cohen's d the combined overall effect was 0.58, [*CI* = 0.40, 0.76], which according to Cohen (1988) is a moderate total effect.

Subjective Measures

The subjective measures effect sizes range was 0.19 to 1.04. The category included subjective well-being measures, workplace satisfaction scores, subjective productivity, and positive and negative affect (emotions). Analysis focusing on the fixed effects at 95% Confidence Interval, using Cohen's d the combined overall effect was 0.57, [*CI* = 0.45, 0.70], which according to Cohen (1988) is a moderate total effect. Of noteworthiness is the finding by Emamjomeh et al. (2020) of Negative Affect in an Immersive Virtual Environment (IVE). The Yin et al. (2020) study did not yield significant results. Rosenbaum et al. (2018) used a video for emersion purposes finding subjective effects.

Comparing the two groups of variables/measures we see that both groups have a similar effect on each other and the overall model.

Findings and Discussion

The present paper aimed to conduct a meta-analytic review of the literature examining both subjective and objective outcomes from biophilic experimentation seeking support for MTC and its potential biophilic effects. Analysing the effect size - a statistical measure used in research to quantify the magnitude or strength of a relationship or the size of an observed effect in a study -

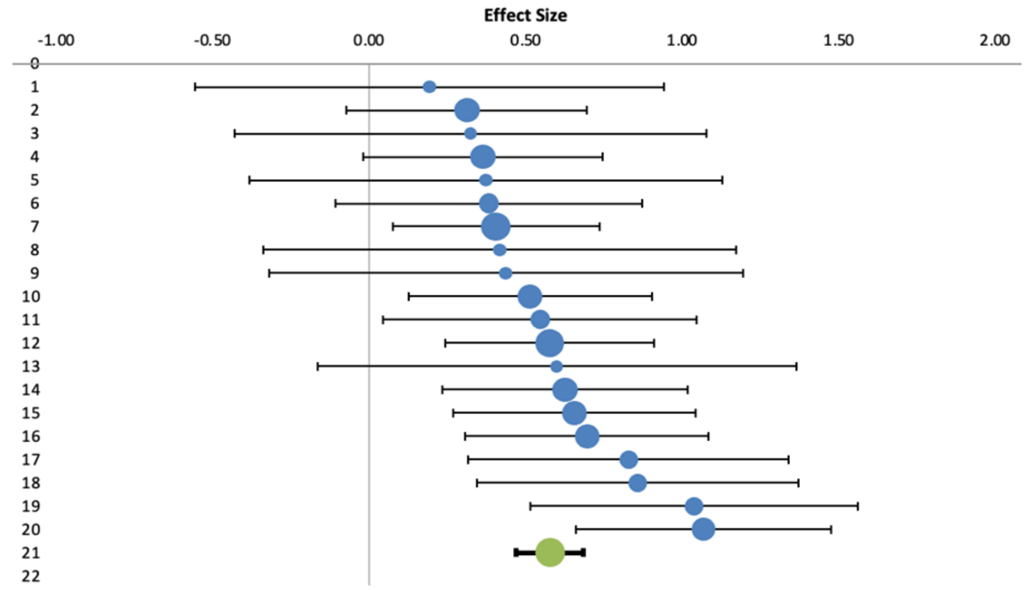

Figure 7. Overall Forest Plot of the overall combined effect sizes from the variables within the studies analysed arranged by descending magnitude.

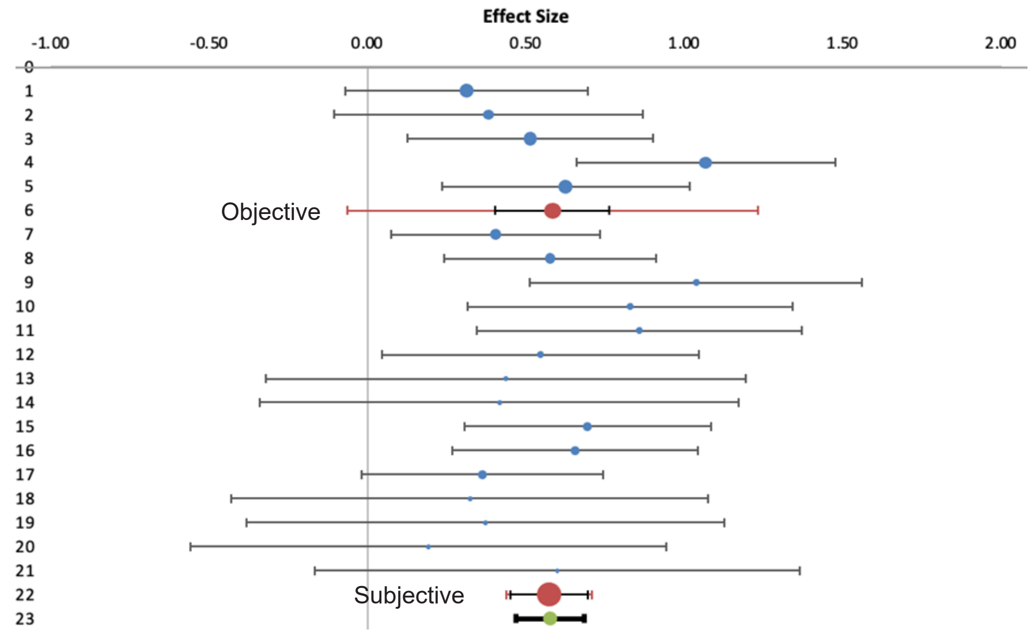

Figure 8. The sub-grouping Forest Plot examines the effects of the magnitude of the objective and subjective variables.

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Table 1. Summary of the studies included in the present review and the indication of the subjective and objective measures.

Author/s	Sample Size	Conditions	Measures	Brief outcome of the study
Shibata and Suzuki (2002)	146 students male and female	The presence of a leafy plant in a room affected subjects' task performance and mood in two kinds of tasks, a sorting task, and an association task.	Subjective measures	The mean differences between the pre and post-task mood evaluations for both the association task and the sorting task Happiness and Calmness were significantly different.
Tsunetsugu et al. (2004)	15 male students	Visual stimulation was given using the two types of living rooms.	Subjective and objectives measures	The designed room did not cause significant change. The two rooms caused no differences in sensory evaluation but did cause significant differences in dynamic states of autonomic nervous activity.
Fell (2010)	119 students male and female	Four office environments were studied: wood and plants, wood and no plants, no wood and plants, and no wood and no plants.	Subjective and objectives measures	Subjects exposed to wood had lower Skin Conductance Levels in the baseline period and lower in all periods of the study. No effect was found with respect to sympathetic activation. Further, there was no evidence of wood-plant interactions. Spectral analysis of Heart Rate Variation data was used to measure parasympathetic activation. No treatment effects were found with respect to parasympathetic activation.
Yin et al. (2020)	100 office workers male and female	Participants were randomly assigned to experience one of four virtual offices (i.e., one non-biophilic base office and three similar offices enhanced with different biophilic design elements) after stressor tasks.	Subjective and objectives measures	For most physiological and psychological measures, the effects of the combination condition were between those of indoor green and outdoor view conditions, although the differences were not significant.
Sanchez et al. (2018)	8 students male	Five-day exposure to greenery, among people exposed to the presence of greenery every day. Compared to those not exposed to greenery each day.	Subjective measures	Correlation analysis results of satisfaction with greenery degree and psychological quantity. Correlation analysis results of the presence of daylight and psychological quantity. There is a significant correlation between the presence of greenery and daylight and the subjective feeling of drowsiness.
Rosenbaum et al. (2018)	Study One 68 male and female shoppers Study Two 220 male and female shoppers	Study One - View a 1.20-minute video that depicts a guided tour of a proposed lifestyle centre in a major South American city. The green version showed natural greenery throughout the lifestyle shopping mall, while the non-green version showed the same lifestyle mall without any natural landscaping features. Study Two - Looked at lifestyle greenery (green vs. not green) and two levels of shopping intent (browsing vs. purposeful shopping).	Subjective measures	Participants rated the perceived restrictiveness of each lifestyle centre and included significant results for the relationship between the two types of retail greenery (green and not green). Within the context of the experiments, this research shows that consumers perceive the restorative potential of biophilia design in the context of a lifestyle centre that employs natural elements such as greenery, fountains, and wildlife (e.g., birds, and butterflies).
Mamore et al. (2020)	55 students male and female	Each participant completed the experiment on two separate days with a few days in between. On 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. A sitting area with views to the outside and a lab space as the biophilic environment and the non-biophilic environment respectively for this study. A virtual biophilic environment and a non-biophilic environment.	Subjective and objectives measures	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.
Lei et al. (2022)	201 office workers male and female	The impacts of biophilic design attributes in offices on workers' health and well-being are examined. A new post-occupancy evaluation (POE) questionnaire is developed for evaluating the biophilic design for workplace health and wellbeing. A questionnaire and field observations of two green building offices in Singapore and Shenzhen, China, are performed. all nine biophilic design attributes for the workplace are employed in the design practice of the selected offices. The below subsections demonstrate the biophilic design strategies for the four design attributes, which are regularly applicable in both offices.	Subjective measures	The results support the importance of biophilic design from the users' perspectives. There is a significant correlation between office biophilic design and the self-reported health of employees.
Adachi et al. (2000)	53 students male and female 5 community members	Participants completed a questionnaire that recorded their initial mood. The mood questionnaire measured six different moods. It consisted of 24 individual visual analogue scales, assessing two negative and two positive feelings for each mood. The moods measured are those which are assessed by questionnaire.	Subjective measures	Few significant mood effects, a room with flowers rated more attractive than the no-plant condition and less 'off-putting' than the foliage condition. There were some specific changes in the moods and feelings of subjects before entering the room compared to their moods and feelings after being under the treatment condition and viewing the video.
Shibata and Suzuki (2002)	70 students male and female.	Randomised experiment with repeated measures of mood, simulated office setting without windows.	Subjective and objec-tives measures	Higher rate of correct response in 2nd task period with plants; no significant effects on mood or fatigue; room with plants rated more silent and smaller.
Etheredge et al. (2014)	298 students male and female	Treatment versus control group study tally areas procedure. Observations occurred during high traffic times based on university catalogue course scheduling.	Subjective measures	There were no differences in stress levels in respondents within different study areas. This could be due to people needing to spend more time surrounded by plants before an effect occurs or people may be prone to study in certain areas out of habit or convenience rather than due to a preference for the area, or due to the temporary nature of usage of the areas studied by the respondents.

provided a standardised way to express the practical significance or meaningfulness of measured aspects independent of the sample size. By synthesising and evaluating a wide range of scholarly articles, this review aimed to consolidate the current understanding of measures used (subjective and objective – physiological and psychological) in determining an approach to assessing the application of mass timber and maximise the benefits from biophilic design treatments.

Aligning with previous meta-analysis (Capaldi et al., 2014; McMahan and Estes, 2015; Gaekwad et.al, 2022; Jason et al., 2022; Gaekwad et al., 2023) the evidence from the present study added further authenticity to the 'biophilic effect' in the built environment situations. The effect, subjective or objective measures, indicate that a moderate effect size is possible from biophilic treatments. Importantly, the results of the study found a moderate effect for objective biophilic effects for timber related to skin conductivity responses in environments containing wood finishes. It should be noted that all except two studies found these effects in 'real world' application experiments as opposed to video or virtual reality. There is a sense from the outcomes of the review that the environments in which the effects are felt may be multi-sensory, and not isolated to audio-visual of virtual environments. Following our meta-analysis, below, we will delve into the discerned themes.

Issues with Experimentation for Biophilic Environments

The numerous research papers reviewed within the present paper all share the common characteristic that the environments created for the various studies have been artificially designed, including not only the VR or IVE environments, however, the use of spaces that are not purposefully designed for long-term use. For example, see Figure 9.

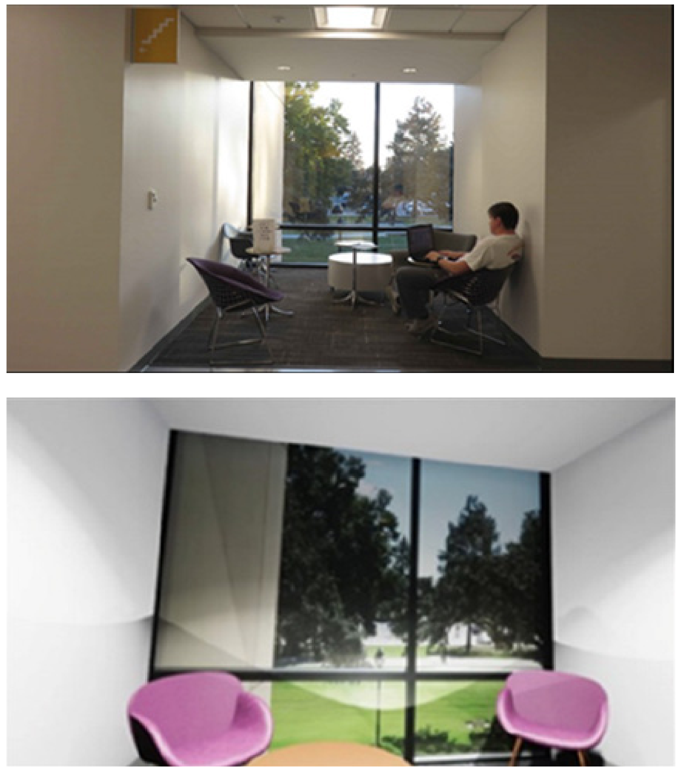

Figure 9. Makeshift and artificial simulations for biophilic designed interior spaces (Emamjomeh et al. 2020).

Compared with environments that have been specifically designed for the purposes of biophilic treatments at the outset and serve as a purposeful intention for the occupancy of a space in a common interior environment, see Figure 10.

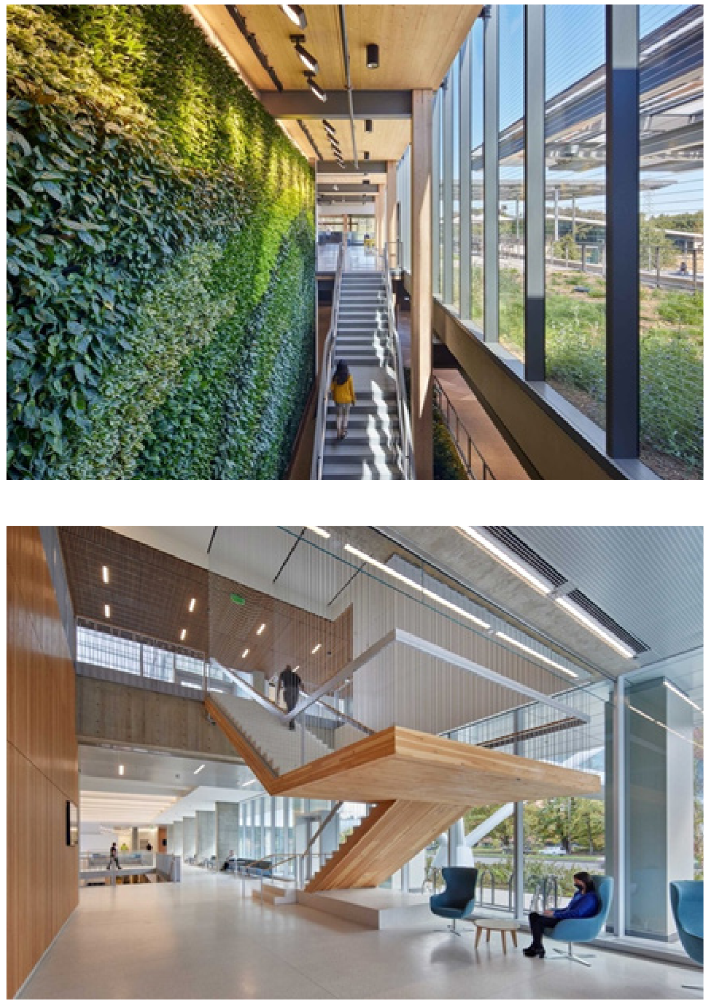

Figure 10. Purposeful biophilic designed interior spaces (Holmes, 2023)

Indeed, Emamjomeh et al. (2020) in their virtual reality environment study concede that it is important to assess the feasibility of recreating certain biophilic elements in laboratory environments, such as through VR or IVE, further adding that there is limited understanding regarding the optimal duration of exposure to natural elements or virtual stimuli for comprehending the impact of biophilic design within immersive environments. Mayer et al.'s study in 2009 suggested that the use of a "virtual" environment was found to be less efficacious both in facilitating participants' contemplation of life issues and in eliciting positive psychological effects. There is a need to conduct more occupancy testing over the long term to assess the impacts of these actual spaces from a biophilic treatment perspective.

Treatment Condition Immersion and Connection to Nature

A substantial difference in the studies review included the degree to which participants were immersed, or not, in the environments and the duration of the immersion. Not only did the immersion and sensory connection to the environment differ based on the use of audio/visual video or virtual reality,

but the time differences also ranged considerably, from a few minutes to repeated use of the environments over multiple days. The inconsistency in exposure to the environment has been acknowledge in other studies (Gaekwad et al., 2022). The connection to the environment in most studies review was as an infrequent observer, sitting or walking through environments. The authors of the present study argue for a standardised design for future testing in environments 'purpose designed and built' for biophilic health benefits, such as those currently trending in mass timber-constructed buildings.

Effects of Biophilic Environments on Occupant Wellbeing

The evidence from the present study suggests that the integration of biophilic design elements in various settings, including workplaces, educational institutions, and healthcare facilities, has shown positive effects on occupant well-being. However, the effect was not consistent in all studies. Research has demonstrated that exposure to nature or natural elements in indoor environments can lead to reduced stress levels, improved attention restoration, and increased overall well-being (Grinde and Patil, 2009; Zhong et al.,2022). The presence of green spaces and access to natural light have been linked to better psychological states, improved memory, and heightened creativity (Wilson, 2017).

Biophilic design interventions, such as incorporating indoor plants, natural materials, and views of nature, contribute to creating more supportive and healthy environments. The outcomes contribute evidence supporting natural materials, such as wood, much like exposure to natural environments, as a likely contributor to stress reduction. The finding of the biophilic effect holds practical implications, suggesting that incorporating natural elements indoors could contribute to evidence-based biophilic designs in settings like offices, schools, and other constructed environments. Whilst not a focus of the present study, biophilic design has gained significance in healthcare settings. Zhao et al. (2022) have shown that exposure to nature and biophilic elements in hospitals and healthcare spaces can have positive effects on patients, promoting healing, reducing stress, and improving wellbeing. Biophilic design interventions in healthcare spaces aim to restore the connection between humans and nature, positively impacting the quality of environments and the health of users. The evidence from this review supports Zhao et al.'s findings.

The Versatility of Wood in Mass Timber Biophilic Structures

As evidenced by the Fell (2010) study, wood is a remarkable creation of nature and holds the power to fulfill triple duty within the built environment by providing biophilic, structural, and aesthetic benefits. Wood is lightweight and robust with a high strength-to-weight ratio making it an excellent choice for construction. The appearance of wood provides a warm and inviting character, which has become commonplace in interior design in our modern era. Unlike plants, wood does not depend on access to windows and natural light, extending its biophilic health benefits even to windowless rooms devoid of natural light or landscapes. For design teams seeking a versatile approach, wood offers a high level of flexibility in both design and application.

Wood, being a natural product aligned with the demand for sustainability, has been used in construction and infrastructure for millennia. It has gained popularity due to its low greenhouse gas emissions compared to traditional building materials, making it a sustainable choice (Kremer and Symmons, 2015). The durability of wood enables its long-lasting use in both residential and commercial buildings, and different types of timber possess varying standards of durability. Moreover, wood boasts impressive strength-to-weight ratios, outperforming materials like steel and concrete in certain scenarios (Alam et al., 2023). Its strength makes it suitable for supporting structures in buildings in a range of classes of buildings, typically mid-rise, circa 12 stories.

One notable advantage of wood is its ability to create a biophilic connection with nature. Natural patterns and textures of wood have been shown to lower blood pressure, heart rates, and stress levels while promoting positive social interactions (Ramadan et al., 2019). The use of wood in interior design aligns with the principles of restorative environmental design, enhancing the well-being of building occupants.

When utilised efficiently, natural materials exude a sense of richness, warmth, and authenticity, engendering a connection with nature that is occasionally invigorating to the tactile senses. Wood is hygroscopic and can exchange moisture within the environments it is located acting like a natural air exchanger and helping maintain humidity and temperature. Wood contributed to a more comfortable indoor environment. Wood offers not only functional benefits but also aesthetic appeal. It is widely admired for its natural beauty and timelessness. Incorporating wood into architectural designs brings the beauty of nature indoors, creating visually pleasing spaces that resonate with occupants. The popularity of wood as a material used in both structural and aesthetic applications in construction has both positive physiological and psychological for occupants.

The present study results align with a suggested approach for Post-Occupancy Evaluation (POE) as a valuable research approach used to assess the effectiveness of biophilic design interventions and measure their impact on occupant well-being. POE approaches focus on collecting data and feedback from occupants after they have spent a significant amount of time in a biophilic environment. The research method allows for a comprehensive understanding of the long-term effects and sustained benefits of biophilic design. POE studies often employ various techniques to evaluate occupant experiences, including surveys, interviews, physiological measurements, and behavioural observations. By analysing occupant feedback and assessing well-being indicators, such as stress levels, productivity, and satisfaction, researchers can quantify the benefits and effectiveness of biophilic design interventions (Barbiero and Berto, 2021).

Measuring occupant well-being in environments treated with a biophilic overlay involves examining factors such as physiological and psychological as well as practical subjective measures, like occupant comfort. Various research studies have explored the relationship between biophilic design and occupant well-being through well-established assessment frameworks and methodologies (Hung and Chang, 2021). These studies contribute to the development of evidence-based guidelines for incorporating biophilic design principles and optimising occupant well-being in diverse settings.

Practical Implications for Mass Timber Constructed Internal Environments

Industry can be assured that evidence from the current and other meta-analytic reviews (Capaldi et al., 2014; McMahan and Estes, 2015; Gaekwad et.al, 2022; Jason et al., 2022; Gaekwad et al., 2023) supports the growing anecdotal wellbeing and health benefits from biophilic treatments applied to interiors in the built environment. Indeed, the degree to which the objective and subjective measures support an overall and combined moderate effect is very encouraging. Given the considerable number of programs and courses currently offering training and education in biophilic design principles, the evidence suggests that such curricula have a burgeoning evidence base. The results of the present review also indicated that the use of wood or timber in biophilic designed and treated environments shows supportive evidence in measures of wellbeing, and the evidence is positive. Extending this notion further, we find support for the use of mass timber as both a structural material and an aesthetic design element (where the timber is expressed/exposed in buildings).

The present study results align with a suggested approach for Post-Occupancy Evaluation (POE) as a valuable research approach used to assess the effectiveness of biophilic design interventions and measure their impact on occupant wellbeing. POE approaches conducted inside recently completed mass timber projects offer an opportunity to focus on collecting data and feedback from occupants after they have spent a significant amount of time in a biophilic environment. The research method allows for a comprehensive understanding of the long-term effects and sustained benefits of biophilic design. By analysing occupant feedback and assessing wellbeing indicators, such as stress levels, productivity, and satisfaction, researchers can quantify the benefits and effectiveness of biophilic design interventions (Barbiero and Berto, 2021).

Limitations

The present study entails several noteworthy limitations. The primary analytical limitation concerns the adaptation of the Meta-Essentials worksheet, which was adjusted for slightly different applications. In our analysis, we explored various factors and measures to derive a statistical effect, deviating from the typical convention of employing a single measure for each study. Consequently, our approach focused on the variable level rather than the study level. As a result, any generalisations drawn from the findings should be made with careful consideration of this distinction.

Another limitation relates to the methodology of the meta-analysis, particularly in terms of interpreting effect sizes and comparing different environments. The interpretation of effect sizes, as originally proposed by Cohen (1988), was applied in this study. However, it remains unclear whether there exists a direct correlation between numerical effect sizes and the wellbeing or health benefits of participants. For instance, it is uncertain whether a large effect size corresponds to a substantial increase in wellbeing experienced by study participants. Therefore, further investigation is needed for an empirical causal association. Furthermore, the analysis aimed to compare the effects of a biophilic environment with the natural environments of a specific location to the studies in this review. Comparisons of these two types of environments may have contributed to a bias effect which over-estimates the actual impacts from the various studies, therefore the experimental design, as per other reviews (Capaldi et al., 2014; McMahan and Estes, 2015; Gaekwad et.al, 2022; Jason et al., 2022; Gaekwad et al., 2023) is required.

In other limitations, regarding MTC buildings and biophilic effects several important considerations exist, the first is that not all MTC buildings have expressed timber. Fire regulations and acoustics considerations govern the type of wall, floor, and support structure construction. Often the mass timber is encased in gypsum or other materials to ensure safe egress or support comfort for the occupants inhabiting the building. An additional consideration is the extend of the building is produced from mass timber, i.e., the percentage of the building that is considered pure or hybrid. It may also be true that timber laminates or other surface interior treatments can achieve a similar effect to mass timber that has been exposed. In totality there remains a paucity of evidence in support of the biophilic treatment effects and its relationship to MTC, further research is required.

Future Research

Future research could look at several aspects that can support and confirm the biophilic treatment effects through the adoption of MTC in construction. The establishment of in-vivo experimentation from within a MTC building is required. More specifically, experimentation that explores the varying nature of exposed timber structure and other biophilic treatments to verify a true effect. Included in the future experiments could be an assessment of other biophilic elements, such as indoor air quality, daylight calculations, viewing nature through windows etc. There is a lot more experimentation required to assess the complexity of biophilic treatments and design in relation to MTC.

Conclusion

The present paper aimed to conduct a meta-analytic review of the literature examining both subjective and objective outcomes from biophilic experimentation seeking support for MTC and its potential biophilic effects. By synthesising and evaluating a select range of scholarly articles, this review aims to consolidate the current understanding of measures used (subjective and objective – physiological and psychological) in determining an approach to assessing the application of mass timber and maximise the benefits from biophilic design treatments. The literature on biophilia and its application in mass timber construction provides valuable insights and highlights the importance of further research in this field.

The key findings and recommendations from the present analytic review include,

- supporting evidence for the biophilic effect of internally built environments for both objective and subjective measures. The magnitude of the effect size was moderate and supported the outcomes of previous meta-analytical reviews. The evidence suggests that the architectural design community should have confidence in the approach to biophilic treatments as a viable option for improving occupant well-being.
- the potential of biophilic design elements, such as the use of wood (the primary ingredient in mass timber), in

promoting the well-being of building occupants. Wood, as a natural and stress-relieving material, has physiological and psychological benefits that make it appealing to users. Biophilic design practices, which incorporate nature-based systems and design cues have the potential to improve health, wellbeing, and performance in the built environment. However, there is a need for further research to quantify the biophilia and health benefits associated with mass timber construction.
- understanding the extent to which biophilic design elements impact human health and well-being in the context of mass timber construction is essential for advancing sustainable and healthy building practices. By quantifying these benefits, researchers and practitioners can provide evidence-based recommendations for the integration of biophilic design principles in future projects. The research can contribute to the development of guidelines and standards that support the implementation of biophilic design strategies in mass timber construction.
- extending the health and well-being aspects, the quantification of productivity improvements in biophilic environments presents a compelling case for enhancing workplace performance, ensuring that employees are not only happier and healthier but also more productive. To build on this, further research should explore long-term studies to assess the sustained impact of biophilic design on critical factors like employee retention, absenteeism, and overall job satisfaction. Such metrics could provide compelling evidence for businesses to invest in timber-based biophilic spaces as part of their core workplace strategy. Additionally, understanding the cognitive benefits—such as enhanced creativity, sharper problem-solving skills, and reduced mental fatigue—could further demonstrate the value of timber construction in fostering high-performance work environments. The integration of biophilic design with broader sustainability goals, like energy efficiency and resource circularity, offers a holistic approach to creating healthier, greener, and more productive built environments that cater to both the human and environmental needs of the future.

The importance of the present study in quantifying the biophilia and health benefits is crucial for the development of mass timber-constructed buildings for several reasons. Firstly, it can help justify the use of wood and mass timber as sustainable alternatives to traditional building materials, such as concrete and steel, by providing evidence of their positive impact on human health and wellbeing. Secondly, it can inform the design process, enabling architects and designers to create spaces that maximise the biophilic response and optimise the health and well-being outcomes for occupants. Lastly, it can contribute to the broader goals of sustainable architecture by demonstrating the potential of biophilic design in achieving sustainability targets, such as enhancing productivity, biodiversity, and circularity.

Declaration of Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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