Frontiers in Computer Science

TYPE Systematic Review
PUBLISHED 04 January 2024
DOI 10.3389/fcomp.2023.1237531

OPEN ACCESS

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RECEIVED 09 June 2023
ACCEPTED 07 December 2023
PUBLISHED 04 January 2024

CITATION
Valentine C (2024) The impact of architectural form on physiological stress: a systematic review. *Front. Comput. Sci.* 5:1237531. doi: 10.3389/fcomp.2023.1237531

The impact of architectural form on physiological stress: a systematic review

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Technological advancements in physiological body sensor networks (i.e., biometric tracking wearables) and simulated environments (i.e., VR) have led to increased research in the field of neuroarchitecture, specifically investigating the effects of architectural forms, defined here as subtle variations in the shape or configuration of the interior built environment, on neurological responses. While this research field is still in its nascent stages, early findings suggest that certain architectural forms may impact physiological stress responses. Physiological stress has, in turn, been implicated in the development of certain diseases, including cardiovascular disease, cancer, chronic kidney disease, non-alcoholic fatty liver disease and autoimmune and neurodegenerative disorders. To aid future research, particularly into the relationship between media architecture and physiological stress, this paper conducts a systematic review following PRISMA-P guidelines on studies that evaluated physiological stress responses to architectural form using clinical biomarkers. The review identifies the specific clinical biomarkers used to evaluate physiological stress responses to architectural forms and the distinct categories of architectural forms that have, to date, been correlated with elevated stress responses: curvature, enclosure and proportion. Although these studies' findings imply that the identified architectural forms influence physiological stress, their generalisability is arguably constrained by several factors. These constraints include the paucity of research in this area, the lack of uniformity in the definition and measurement of these architectural forms, the varying contextual settings, the unisensory approach of research methodologies, and the duration of exposure under evaluation. The review concludes that clinical biomarkers may be used to measure the impact of architectural form on physiological stress; however, future research should strive for standardized approaches in defining and measuring architectural forms in order to increase the transferability and robustness of results.

KEYWORDS

architecture, architectural health, physiological stress, clinical biomarkers, architectural form, neuroarchitecture

1 Introduction

In developed nations, individuals spend over 90% of their time indoors (Schweizer et al., 2007). In some areas, such as the UK, this increases to an average time spent indoors of 95.6% (Schweizer et al., 2007). Moreover, certain vulnerable segments of the European population, such as the elderly, infants, young children, and those with compromised immunity, could potentially allocate 100% of their time indoors (Vardoulakis et al., 2015, cited in Vardoulakis et al., 2015). As people increasingly spend a significant portion of their time in and around the built environment, it becomes crucial to understand how architectural design choices may impact human physiology.

Technological innovations in physiological body sensor networks and simulated environments (virtual reality or VR) have provided researchers in the field of neuroarchitecture with the tools to measure the impact of architectural design on physiological responses (Borgianni and Maccioni, 2020). Researchers have examined a variety of neurological responses to a wide range of architectural features,[1] such as architectural styles (Choo et al., 2017; Coburn et al., 2017), spatial geometry (Vartanian et al., 2013, 2015; Shemesh et al., 2017, 2021), height and enclosure (Fich et al., 2014; Vartanian et al., 2015; Shemesh et al., 2017, 2021), architectural façade and landmark recognition (Rounds et al., 2020), interior space design (Fich et al., 2014; Banaei et al., 2017, 2019), lighting (Shin et al., 2015; Ergan et al., 2019; Lu et al., 2020), ambient conditions (Choi et al., 2019; Guan et al., 2020), materiality (Tsunetsugu et al., 2002) and chromaticity (Küller et al., 2009; Ergan et al., 2019).

Recently, researchers have begun to use clinical biomarkers to empirically examine physiological stress responses to the built environment (Guidi et al., 2021). Physiological stress responses refers to the intricate array of bodily adjustments initiated when an individual encounters physical or psychological stressors capable of disturbing the body's equilibrium, known as homeostasis (Chu et al., 2023). Clinical biomarkers (sometimes referred to as "psychophysiological measures") are objective empirical measurements of bodily functions that predict clinically relevant processes (Aronson and Ferner, 2017). For the purposes of this paper, these objective empirical measurements are simply referred to here as "biomarkers." The most common biomarkers used to measure physiological stress responses are blood pressure, heart rate and respiratory rate increases, skin conductance and body temperature, salivary cortisol, and brain activity (Persiani et al., 2021). These techniques have all been used in the field of neuroarchitecture. A number of neuroarchitecture studies suggest that visual exposure to variations in architectural form, defined here as subtle variations in the geometric shape or configuration of the interior built environment, may mediate physiological stress responses (Kim and Kim, 2022).

These findings are significant, given the causal relationship between physiological stress responses and systemic inflammation, the latter of which is associated with higher morbidity and mortality rates (Mariotti, 2015). Emerging research in the field of neuroimmunology suggests that physiological stress responses may result in long-term physiological damage (O'Callaghan, and Miller, 2019) and the development of a number of severe health conditions, including neuroinflammatory disorders (Dhabhar, 2008; Frank et al., 2019). Physiological stress responses engage in a bidirectional dialogue between the central nervous system (responsible for physiological stress responses) and the immune system (responsible for inflammatory processes in the body, including neuroinflammation; Munhoz et al., 2008; DiSabato et al., 2016). Physiological stressors have been found to induce alterations in immune function (Wohleb and Godbout, 2013) via the nervous system (Frank-Cannon et al., 2009; Grippo and Scotti, 2013), resulting in proinflammatory responses in the peripheral organ systems (i.e., liver, kidneys, lungs, and heart) and the brain (Lurie, 2018; Stenvinkel et al., 2021). Conversely, reductions in physiological stress have been found to mitigate these negative impacts by reversing inflammation via the same pathways (Rosenkranz et al., 2016).

To date, there has been a paucity of research into our physiological response to media architecture.[2] Media architecture employs dynamic architectural elements, such as programmable lights and digital surfaces, creating structures that are capable of dynamically altering their form and appearance in response to various circumstances (Foth and Caldwell, 2018). The emergence of media architecture may open a window of opportunity for reducing physiological stress induced by specific architectural forms. For example, if architectural forms can indeed induce physiological stress, the interactive and dynamic nature of media architecture could be strategically utilized to counteract these effects. The integration of digital technologies allows the creation of environments that adjust according to their occupants' physiological responses. Consider a room design where wall curvature and proportions could dynamically adapt to its occupants' physiological stress levels, based on real-time feedback from biometric sensors. This adjustment could be as simple as the room appearing more spacious or the walls adopting a softer curvature. Given the growing trend toward biophilic design, which promotes our innate affinity for natural elements (Salingaros, 2019), digital responses could incorporate elements reminiscent of natural environments. The interplay of sunlight and shadow, the gentle movement of leaves, or the visual impression of natural materials could all be digitally replicated and adjusted to promote wellbeing (Yin et al., 2020).

However, it is essential to recognize that the integration of media architecture may have the potential to trigger our physiological stress responses. As digital technologies become more immersive, the risk of exacerbating physiological stress responses increases incrementally. Media architecture's dynamic nature might overstimulate occupants, causing disorientation or discomfort (Valentine, 2023a). For instance, the occurrence of an excessive multiplicity of sensory stimuli has the potential to precipitate sensory overload. Sensory overload, or sensory overstimulation, is a neurological phenomenon characterized by the excessive stimulation of one or more sensory modalities, resulting in the sensory system's inability to adequately process and respond to the incoming sensory information (Scheydt et al., 2017). This condition can be triggered by an intense, prolonged, or complex array of sensory stimuli, and is often associated with certain neurodivergent conditions, such as autism spectrum disorder (Balasco et al., 2020), post-traumatic stress disorder (Harricharan et al., 2017), attention deficit hyperactivity disorder and sensory processing disorder (Miller et al., 2012). In these instances, it is possible that the dynamic, and often unpredictable, architectural elements used in media architecture may increase stress responses rather than alleviating them. To the best of the author's knowledge, no

1 The term "architectural features" here refers to specific characteristics of the built environment, i.e., thermal comfort, lighting and material composition.

2 However, see Zielinska-Dabkowska (2014), this study investigated concerns regarding media architecture negatively affecting urban nighttime environments.

research has directly examined physiological stress responses to media architecture.

To aid future research into the impact of architectural form on physiological stress, this paper conducts a review of studies that isolate and test physiological stress responses to specific architectural forms using clinical biomarkers. As this review is limited to considering the geometric shape or configuration of the interior built environment, the review does not consider architectural features such as lighting, materiality, thermal comfort, or color. Although these features invariably impact human physiology and are worthy of further investigation, they remain outside the scope of this review. The review aims to identify (i) the clinical biomarkers used to measure physiological stress responses to architectural form, (ii) categories of architectural forms that are correlated with elevated stress response, and (iii) limitations with existing research methods.

The review is conducted following the Preferred Reporting Items for Systematic Reviews and Meta-Analysis Protocols (PRISMA-P) guidelines. PRISMA-P is a widely used methodological and analytical framework for systematic reviews that maintains consistency in systematic review methods across health disciplines. In brief, the review reveals that electroencephalography [Banaei et al., 2017; Kim et al., 2021 (Alpha to Beta Wave Ratio); Shemesh et al., 2021; Cruz-Garza et al., 2022], Functional Magnetic Resonance Imaging (Vartanian et al., 2015), Heart Rate Variability (Fich et al., 2014; Abd-Alhamid et al., 2020; Li et al., 2022), Galvanic Skin Response (Abd-Alhamid et al., 2020; Shemesh et al., 2021), Pupil Dilation (Shemesh et al., 2021), and Salivary Cortisol (Fich et al., 2014; Li et al., 2022) are the primary clinical biomarkers engaged. The review further identifies curvature (Banaei et al., 2017; Shemesh et al., 2021; Li et al., 2022), proportion (Kim et al., 2021; Shemesh et al., 2021), and enclosure (Fich et al., 2014; Vartanian et al., 2015; Abd-Alhamid et al., 2020; Kim et al., 2021; Cruz-Garza et al., 2022) as categories of architectural forms that have been linked to physiological stress. However, it is difficult to definitively categorize each architectural form measured or its impact on physiological stress given the lack of uniformity in the definition and measurement of these architectural forms, indicating variations in interpretive frameworks. Moreover, the transferability of these findings are further limited by the contextual and behavioral nature of architectural experiences.

The analysis process was divided into four stages. First, studies investigating stress responses to architectural forms were selected for inclusion. Second, the clinical biomarkers and methods used to examine physiological stress responses in these studies were gathered. Third, the architectural features examined in these studies were isolated. Fourth, robustness of the methodological approaches engaged to measure physiological stress responses to architectural forms were analyzed. To begin, the following section sets out the methodology employed and the limitations of this review.

2 Methodology

In the present review, PRISMA-P was used to analyse controlled studies which isolated and tested physiological stress responses to individual architectural forms (i.e., subtle variations in the geometric shape or configuration of the interior built environment) to the exclusion of characteristics such as lighting, materiality and biophilic design. Variations in architectural form in both physical and virtual environments were considered.

PRISMA-P is a research protocol developed to enhance the transparency, quality and rigor of systematic reviews and meta-analyses (Shamseer et al., 2015). As Shamseer et al. (2015, p.1) state "protocols of systematic reviews and meta-analyses allow for planning and documentation of review methods, act as a guard against arbitrary decision making during review conduct, enable readers to assess for the presence of selective reporting against completed reviews, and, when made publicly available, reduce duplication of efforts and potentially prompt collaboration." For the present review, PRISMA-P was particularly helpful in clearly defining the population of interest (i.e., healthy individuals), the intervention (i.e., the particular architectural forms and settings), comparator (i.e., no restriction was placed) and outcomes (i.e., impact on physiological stress response as measured using clinical biosensors such as EEG, HRV and GSR).

However, examining the impact of architectural form on physiological stress responses presents a multifaceted challenge, and its exploration is not without limitations. PRISMA-P is primarily designed for clinical and health-related studies, and its adaptation to architectural research might inadvertently overlook critical contextual factors intrinsic to the built environment. Architectural forms' influence on physiological stress responses is influenced by various variables, including cultural, social, and psychological dimensions that might not fit neatly into the PRISMA-P structure. Therefore, researchers should approach this investigation cautiously, acknowledging the need for a more tailored and interdisciplinary approach to fully capture the intricate interplay between architectural design and human neurophysiology. However, for the specific purposes of this review, PRISMA-P provided a rigorous framework to identify, categorize and analyse relevant studies.

2.1 Review scope

A search strategy was developed using the PRISMA-P protocol under the headings of Population, Intervention, Comparison, and Outcome (PICO) (Moher et al., 2015).

a. Population—Included populations consisted of healthy individuals. No demographic restrictions were placed on the population.
b. Intervention—This review identified papers which evaluate stress responses to architectural form (i.e., geometric configuration). Studies which evaluated indoor environmental quality (i.e., auditory or environmental noise, thermal comfort, air quality or presence of volatile organic compounds and lighting), street design (i.e., traffic routing, sidewalk configuration), biophilia design or color were not considered. Studies which evaluated the impacts of urban greenery or exposure to indoor plants were also not considered. Additionally, studies which grouped intervention characteristics together were also not considered. For example, Ergan et al. (2019) measured the combined responses of lighting, signage,

TABLE 1 Search criteria and linguistic variations for topic "measuring the physiological response to the built environment using biosensors".

Key terms	Term 1	Term 2	Term 3
Key concepts	Physiological response	Built environment	Biosensors
Related search terms	Physiological w/3 Response OR Physiological w/3 effect OR Physiological w/3 stress	Built environment OR Architecture OR Facade* OR Interior* OR Building design	Biosensors OR EEG OR Body sensor OR Biometric

and light bounce, while Jin and Juan (2021) measured the impacts of Feng Shui, which incorporates a combined number of architectural criteria. Future research may wish to consider the impacts of these combined and confounding variables on stress responses; however, they remain outside the scope of this review. Both virtual and physical environments were considered.

c. Comparator—No restriction was placed on the control/comparator. This means that the selection of the control or comparator group was left unrestricted, allowing for a wider range of options and variations in the studies being reviewed. This approach could enhance the generalizability and variability of the findings in the systematic review.
d. Outcome—Studies which measured stress responses using clinical biomarkers (i.e., EEG, fMRI, HRV, GSR, pupil dilation, salivary cortisol) were included. Self-reported stress levels were excluded.

Study selection was undertaken with the removal of duplicates and the initial screening of the title and abstract against eligibility criteria using a checklist. This was achieved using the web-based Rayyan tool.

2.2 Search strategy

Three electronic bibliographic databases were searched: SCOPUS, Web of Science and Science Direct. PubMed was also searched, though it was not included in the formal database search due to algorithmic deviations in search criteria. Hand searches of reference lists of included studies were also made. Google Scholar was searched for additional gray literature. The review inclusion criteria were for studies in English conducted between January 2013 and January 2023. A table of relevant key conceptual search terms is displayed in Table 1.

3 Results

Results from databases and other sources, including gray literature, identified $n = 1,334$ potentially relevant studies after removal of duplicates. These results can be broken down as follows: PUBMED ($n = 330$), Science Direct ($n = 273$), SCOPUS ($n = 551$), Web of Science ($n = 180$) and records identified through other sources i.e., Google Scholar, cited articles etc. ($n = 152$). These records were screened by title and abstract ($n = 269$). Following full-text screening, $n = 9$ sources were included for data extraction. From these sources, the relevant clinical biomarkers and architectural forms were identified. The search process is summarized in the PRISMA-P flow diagram below (Figure 1).

4 Findings

To recall, the aim of this systematic review was three-fold: (i) to determine the specific clinical biomarkers utilized for evaluating physiological stress responses to architectural forms (ii) to identify distinct categories of architectural forms that are correlated with elevated stress responses, employing clinical biomarkers, and (iii) to analyse the robustness of the methodological approaches engaged to measure physiological stress responses to architectural forms. This section presents an overview of the review findings.

4.1 Measurement technique

The review revealed the clinical biomarkers and biosensors most commonly used to measure stress responses to particular architectural forms (see Table 2 below). The most common biomarkers used to measure stress responses are pupil dilation, heart rate and heart rate variability (HRV), skin conductance and body temperature, salivary cortisol, Galvanic Skin Response (GSR), brain activity, and functional Magnetic Resonance Imaging (fMRI) (Persiani et al., 2021).

Increased stress responses may be indicated by greater pupil dilation, which shows heightened cognitive and emotional arousal, a reduced HRV, increased levels of the stress hormone - salivary cortisol, and changes in GSR (with stressors resulting in increases in skin conductance levels). When it comes to measuring brain activity, EEG is used to measure activity in the brain waves—alpha, beta, delta, gamma, and theta. Changes in EEG activity indicating stress include increased beta wave activity and decreased alpha wave activity. A high ratio of alpha to beta waves (RAB) suggests a more relaxed state, while a low ratio indicates a more alert and active state. Therefore, an increase in beta waves relative to alpha waves is often interpreted as an indicator of heightened arousal or stress. Theta waves are typically observed during periods of intensified mental and emotional activity, while gamma waves are associated with heightened arousal states, including anxiety and fear. Finally, fMRI scans measure neurological activity by detecting changes associated with blood flow (Glover, 2011). Neural activity and energy metabolism (i.e., cerebral blood flow) are coupled, meaning that when a region of the brain is engaged, blood flow to that area increases (Logothetis et al., 2001). In short, with fMRI, it becomes possible to identify which area of the brain is being activated during a particular activity. The changes that indicate increased stress are increased activation in regions such as the amygdala, insula, and anterior cingulate cortex, which are associated with the processing of emotional and stress-related stimuli.

4.2 Architectural forms identified

The review identified the most common architectural stimuli used to assess physiological stress responses to architectural

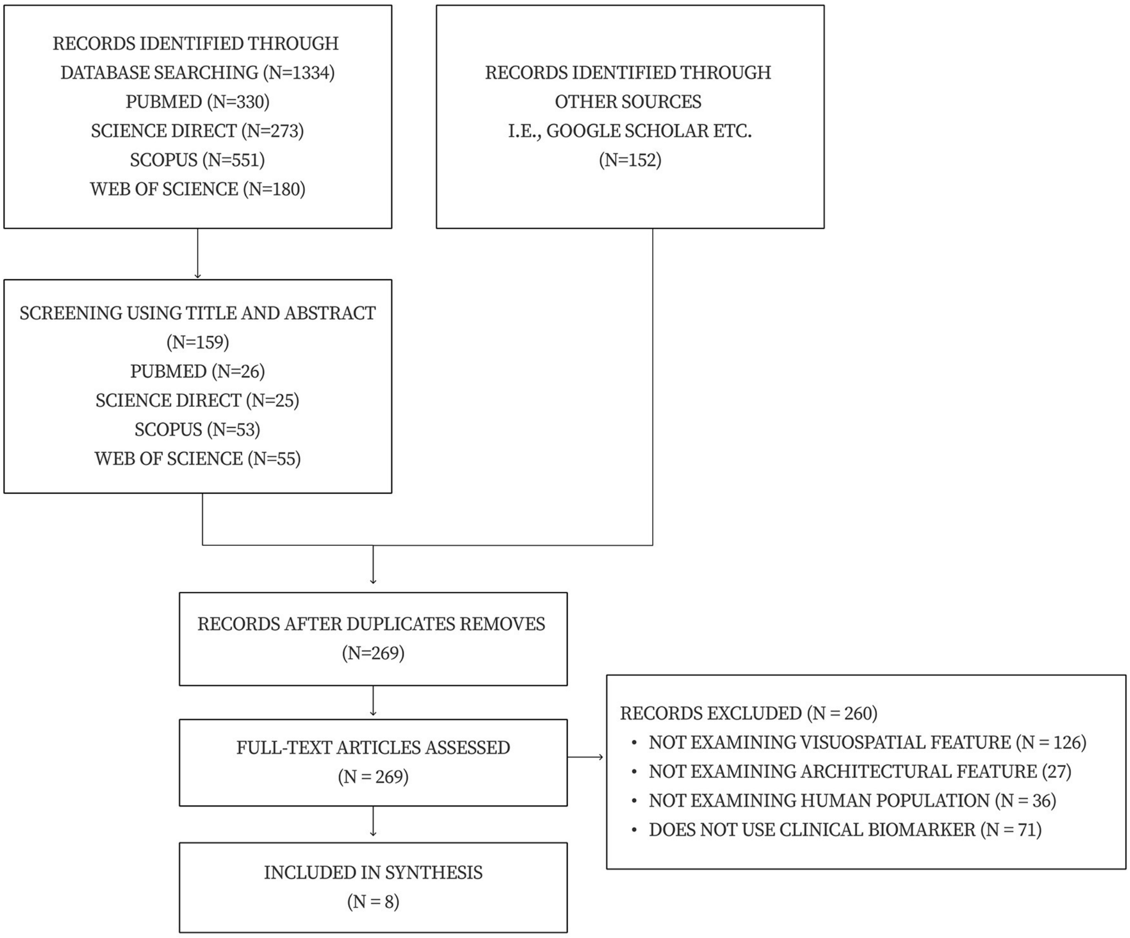

FIGURE 1
PRISMA-P flow diagram.

forms (Table 3). Furthermore, it identified the most frequently evaluated categories of architectural forms that exhibit a notable correlation with augmented stress reactions, as confirmed by the assessment of clinical biomarkers (Table 4). The identified architectural forms have been separated into three categories using engineering terminology: curvature, proportion, and enclosure. For the purposes of this review, engineering terminology was adopted as the precise definition of the parameters used to characterize particular architectural forms (and variations in same) varied across individual studies (discussed further below). While engineering terminology may not be homologous to the identified architectural variables it is suitably analogous and provides a useful means to categorize these variables in a coherent fashion.

However, given the inherently contextual nature of architecture, the application of engineering terminology requires careful consideration. For instance, curvature, as per engineering standards, signifies "the rate of directional change of a curve relative to its distance along the curve" (Whitman College, 2023). Nonetheless, the term curvature can encompass diverse architectural designs, such as the juncture of walls and ceilings in a vaulted structure, or the design of the header in an arched window. Despite these shortcomings, engineering terminology (curvature, proportion, and enclosure) was purposefully employed to establish a coherent framework for presenting the outcomes.

4.2.1 Curvature

To recall, the linear or curvilinear quality of walls within architectural structures can be defined as "the rate of change of direction of a curve with respect to distance along the curve" (Whitman College, 2023). Among the studies reviewed, three studies (Banaei et al., 2017; Shemesh et al., 2021; Li et al., 2022) measured stress responses to variations in curvature using clinical biomarkers.

Shemesh et al. (2021) examined the physiological and emotional responses of 112 participants to 27 different virtual scenes that varied in scale, curvature, proportion, and protrusion using multiple clinical biomarkers. The study measured EEG (Beta Waves), pupil dilation, and GSR. The architectural environment consisted of a white room without ornamentation or openings. The study defined the degree of curvature in the VR environment by combining the criteria of zero curvature and asymmetry. The degree of wall and ceiling curvature of the interior room

TABLE 2 Identified clinical biomarkers utilized for evaluating physiological stress responses to architectural forms.

Clinical biosensor	Definition	Identified studies
Electroencephalography (EEG)	EEG is a technique used to measure and record the electrical signals produced by neurons in the brain by placing electrodes on the scalp. EEG is commonly employed in medical and research settings to study brain function, diagnose neurological disorders, and monitor sleep patterns	Shemesh et al., 2021 (Beta Wave) Banaei et al., 2017 (Theta Wave) Kim et al., 2021 (Alpha to Beta Wave Ratio) Cruz-Garza et al., 2022 (Alpha Wave)
Functional magnetic resonance imaging (fMRI)	fMRI is a neuroimaging technique that measures brain activity by detecting changes in blood flow and oxygenation. By employing strong magnetic fields and radio waves, fMRI scans generate detailed images of the brain's structure and identify areas that are active during specific tasks or cognitive processes. It is commonly utilized in research and clinical settings to study brain function and understand neurological conditions	Vartanian et al., 2015
Heart rate variability (HRV)	HRV refers to the variation in the time intervals between successive heartbeats. HRV is considered an indicator of the autonomic nervous system's activity and reflects the adaptability and flexibility of the cardiovascular system. It is frequently employed in research and clinical applications to assess the health and function of the cardiovascular system	Abd-Alhamid et al., 2020 Fich et al., 2014 Li et al., 2022
Galvanic skin response (GSR)	GSR, also known as Skin Conductance Response (SCR), measures the electrical conductance of the skin, which changes in response to emotional or physiological stimuli. It is based on the principle that sweat glands become more active when a person experiences emotional arousal or stress, resulting in increased skin conductance	Shemesh et al., 2021 Abd-Alhamid et al., 2020
Pupil dilation	Pupil dilation is the expansion of the black part of the eye (the pupil), allowing more light to enter. It's relevant to stress responses as increased pupil dilation is often associated with the body's "fight or flight" reaction, indicating heightened arousal and readiness to respond to potentially threatening situations	Shemesh et al., 2021
Salivary cortisol	Salivary cortisol is a steroid hormone found in saliva that is produced by the adrenal glands in response to stress. Its measurement in saliva provides a non-invasive way to assess the body's physiological stress response, aiding in understanding and monitoring stress-related effects on health	Li et al., 2022 Fich et al., 2014

was controlled using a script in Grasshopper (software tool). Specifically, the interior walls and ceiling were adjusted from "orthogonal to round" and "sharp to curvy," measured on the basis of a scale between 0 and 4. The findings of the study demonstrated a positive correlation between minimal wall curvature and increased physiological stress. The participant's exhibited augmented pupil diameter and an increase in peak measurements of maximal GSR amplitude when exposed to low curvature. However, no statistically significant results were reported concerning Beta Wave activity. Collectively, these outcomes imply that minimal wall curvature might be linked to an elevated physiological stress response.

An earlier study by Banaei et al. (2017) measured physiological responses to variations in architectural form, including degrees of wall curvature. Twenty-five different form clusters were extracted from 343 interior images of living rooms from different architectural epochs with varying architectural styles. To assess the impact of the stimuli, 17 participants' brain activity was measured using EEG as they walked through a VR environment. Unlike Shemesh et al. (2021), which used a curvature scale between 0 and 4, curvature in this study was defined using a binary: linear or curved. Linear was defined as a 3D solid with a width $<$20 cm, that was attached to another surface by its large face. The definition of curvature was not explicitly stated, however, the degree of curvature appeared to relate to either a curved connection between the ceiling and walls, curved archways, or a curved wall. While the study did not directly measure stress responses the findings suggest that greater curvature resulted in higher pleasure and emotional arousal rates, these were reflected in higher theta wave activity of the anterior cingulate cortex (ACC). Based on the findings of this study, it can be inferred that the anterior cingulate cortex (ACC) plays a role in the cognitive processing of architectural experiences. However, the specific association between theta wave activity and physiological stress remains inconclusive as theta wave activity is associated with a range of emotional arousal, including fear and anxiety (Lapomarda et al., 2022).

Most recently, Li et al. (2022) investigated the effects of transitional spaces on stress recovery using a VR environment. Forty participants were randomly assigned to one of three conditions: a curvilinear transitional space, a linear transitional space, or a control condition with no transitional space. Li et al. (2022) differed from both Banaei et al. (2017) and Shemesh et al. (2021) in that they assessed transitional spaces (partly indoor and partly outdoor). Additionally, Li et al. (2022) defined "curve" as having a round shape according to the Oxford Learner's dictionaries. Two transitional spaces were assessed: a cafe and a plaza. The area of the cafe space included a range of elements, like overhead weather shelters, benches, tables, planters, flooring, and lights. Within this cafe space, two distinct environments were established: a linear environment (B linear) and a curved environment (B curved). Similarly, the transitional area of the plaza featured overhead shelters, flowerbeds, and landscape treatment. In the plaza space, analogous to the cafe space, two environments were formed: a linear environment (A linear) and a curved environment (A curved). The study distinguished between linear and curved environments based on the predominant shape of their components. Stress responses were assessed using the Trier Social Stress Test (TSST), which included measures of salivary cortisol, heart rate variability, and subjective stress ratings. The study found that both curvilinear and linear transitional spaces had a positive effect on stress recovery compared to the control condition.

TABLE 3 Identified architectural stimuli utilized for evaluating physiological stress responses to architectural forms.

Architectural stimuli	Definition	Studies identified
Virtual reality (VR)	Virtual reality (VR) is a technology that utilizes computer-generated simulations to create immersive, three-dimensional environments that can be explored and interacted with by a person. VR typically requires wearing a head-mounted display that tracks the user's head movements, providing a realistic sense of presence and immersion in the virtual world	Shemesh et al. (2022) Li et al., 2022 Kim et al. (2021) Shemesh et al. (2021) Banaei et al. (2017) Cruz-Garza et al. (2022)
2D images	"2D" image refers to a visual representation that exists solely within the dimensions of width and height, lacking depth or three-dimensional spatial characteristics, and is typically displayed on a flat surface or plane	Fich et al. (2014) Vartanian et al. (2015)
Physical reality	Physical reality features architectural designs which are both constructed using tangible materials and physically inhabitable. This is a preferable method of architectural analysis as it encompasses the multisenory nature of the architectural experience	Abd-Alhamid et al. (2020)

TABLE 4 Identified categories of architectural forms that have demonstrated a correlation with elevated stress responses.

Architectural form	Utilized in study
Curvature	Banaei et al., 2017; Shemesh et al., 2021; Li et al., 2022
Proportion	Kim et al., 2021; Shemesh et al., 2021
Enclosure	Fich et al., 2014; Vartanian et al., 2015; Abd-Alhamid et al., 2020; Kim et al., 2021; Cruz-Garza et al., 2022

However, no significant difference in physiological activity was recorded between the curvilinear and linear transitional space types. As a result, further scholarly investigation is merited.

4.2.2 Proportion

Proportion is defined as "the relationship between one thing and another in size, amount, or degree" (Merriam-Webster, 2023), and is indicated in architectural design by variations in ceiling height, aspect ratio, and scale. The following two studies examined the impact of proportion on physiological stress using clinical biomarkers (Kim et al., 2021; Shemesh et al., 2022).

In Kim et al. (2021), an arousal response was measured using EEG and virtual reality, exploring changes in ceiling height, window area ratio, and aspect ratio in 33 female participants who experienced a private postpartum care room via virtual reality, during which an Alpha/Beta Wave (RAB) ratio was recorded and a self-report questionnaire was administered. A reduced ratio of alpha/beta (RAB) typically indicates higher stress levels or reduced relaxation states, whereas an increased RAB generally signifies lower stress levels and reduced arousal responses. Aspect ratio "means the ratio between the length and the width of a plane" (Kim et al., 2021, p. 7). Two scenarios with varying aspect ratios were created. The aspect ratio of Type A was 1:1.6 (3 m × 4.81 m), where the space was long seen from the door, while the aspect ratio of Type B was 1.6:1 (4.81 m × 3 m), where the space was wide. The precise ceiling height was defined as the height from the floor finish to the ceiling finish. Three ceiling height variations were defined: 2.3 m, 2.7 m, and 3 m. Window ratio was determined using the following formula: window area/(exterior envelope wall area + window area) × 100%. Five types of window ratios were defined: 20%, 40%, 60%, 80%, and 100% (discussed further in 4.2.3 below). The study found that in a room with an aspect ratio of 1:1.6, the window ratio of 60% induced the least arousal response when the ceiling height was 2.3 m. However, when the ceiling heights were 2.7 and 3.0 m, the window ratio of 80% induced the least arousal response. In a room with an aspect ratio of 1.6:1, when the ceiling heights were 2.3 and 2.7 m the window ratios of 100 and 80% induced the least arousal response, respectively. The window ratios induced the least arousal response when the ceiling heights were 2.3 and 2.7 m, whereas the window ratios of 40%, 60%, and 100% induced comparable arousal responses when the ceiling height was 3.0 m.

As noted above, Shemesh et al. (2022) conducted a study on the emotional impact of architectural geometries using biometric measurements: pupil dilation, galvanic skin response and EEG. Their findings regarding proportion found narrow spaces (2m × 4 m × 4 m) were associated with larger mean pupil diameter and maximal pupil diameter, indicating increased physiological stress. In addition, the study found heightened Beta Wave activity in narrow virtual environments. These results suggest that narrow spaces elicit greater physiological stress responses than wide spaces (6 m × 4 m × 4 m).

4.2.3 Enclosure

In the present context, the term "enclosure" pertains to the diverse configurations and dimensions of windows within a building. It specifically encompasses the size and arrangement of windows within the building envelope or facade. However, there is an intersection between proportion and enclosure. For example, specific room proportions, such as narrower dimensions, can amplify the sense of enclosure. Additionally, certain studies (Vartanian et al., 2015; Kim et al., 2021; Shemesh et al., 2021) manipulated both proportion and enclosure concurrently, highlighting their interconnected nature. The following five studies examined the impact of enclosure on physiological stress using clinical biomarkers (Fich et al., 2014; Vartanian et al., 2015; Abd-Alhamid et al., 2020; Kim et al., 2021; Cruz-Garza et al., 2022).

Fich et al. (2014) utilized a virtual Trier Social Stress Test to examine salivary cortisol, a stress hormone, and HRV responses in 49 healthy male participants with no architectural training, aged 19 to 31. Subjects were placed in two virtual environment test rooms and made to undergo three psychosocial stress-inducing activities (an incomplete instruction by the committee about one of the tasks, preparing and presenting a speech, and taking a basic maths exam), each of which lasted for 5 min. Room one had no openings, while room two had three large openings with a view of a simple horizon line. The specific size of the openings were not reported. The participants in the enclosed space responded with pronounced increases in salivary cortisol (73% increase), heart rate (15.3% increase) and decreased recovery speed, as compared to the participants in open rooms. The results indicate increased acute stress responses in enclosed architectural forms.

Subsequently, Vartanian et al. (2015) examined the effects of ceiling height and perceived enclosure areas on neurological activity using fMRI scans. The study examined the neural activity of 18 participants as they were exposed to 200 two-dimensional (2D) photographs of architectural forms. The study reported that "half of the spaces had high ceilings and the other half had low ceilings. Similarly, half of the spaces were enclosed and the other half open. This resulted in the following four conditions: open high ceiling, open low ceiling, enclosed high ceiling, and enclosed low ceiling" (Vartanian et al., 2015, p. 14). However, similarly to Fich et al. (2014), the explicit definitions or dimensions for "high ceiling," "low ceiling," "enclosed," and "open" were not provided. The results indicated that the enclosed rooms elicited increased acute activation in the anterior midcingulate cortex (aMCC), which receives direct input from the amygdala, a part of the brain that governs fear responses. Although the aMCC receives inputs from many areas of the brain and is engaged in various cognitive and emotional integration processes, the author states that "Vogt's (2005) analysis of 23 neuroimaging studies showing peak activations within the cingulate gyrus demonstrated that the specific region activated in the present study is associated with processing fear" (Vartanian et al., 2015, p. 16). Put simply, it appears that enclosed rooms may trigger a fear based stress response. While Vartanian et al. (2015) did explore aspects of proportion, their empirical observations (i.e., activated structures involved in visuospatial exploration and attention in the dorsal stream) remain unassociated with physiological stress responses, consequently precluding their inclusion within the present review.

More recently, Abd-Alhamid et al. (2020) utilized skin conductance, heart rate, and HRV to assess the restorative effect of different levels of enclosure by providing a window view observation period after a stressful task on 32 participants. Unlike the studies outlined above, Abd-Alhamid manipulated the degree of enclosure by changing the viewing distance from the window as opposed to the size of the opening (Vartanian et al., 2015) or the number of openings (Fich et al., 2014). Instead, the window view was observed from three different viewing locations: close (0.8 m), middle (2.18 m), and far (3.55 m). The window measured 1.4 m × 1.4 m on a wall measuring 3.3 m × 2.85 m. A windowless environment was used as a baseline. Abd-Alhamid et al. (2020) detected significant changes in skin conductance, with higher values observed when participants viewed objects up close compared to when they viewed objects at middle and far distances. Moreover, decreased indicators of heart rate and HRV were observed in the middle and far viewing locations when contrasted with the close viewing location. These physiological changes suggest that the size of window views can have a significant impact on the stress-recovery process and overall wellbeing of building occupants, with smaller windows resulting in increased physiological stress responses.

Building on the previous research, Cruz-Garza et al. (2022) conducted a study to evaluate the effects of window positioning, quantity, and size, on human stress and anxiety levels using EEG in classrooms. Biometric measurements of stress responses were taken from participants during a VR experience and then integrated into a normative dataset composed of the participants' backgrounds and other demographic information. Similar to Fich et al. (2014) and Cruz-Garza et al. (2022) changed the number of windows, as opposed to the size of a single window. Subjects fitted with VR were exposed to four room types, each for a period of 2 min: (i) windowless; (ii) one window; (iii) two windows, and (iv) windowless but with an increased room width. Three different window arrangements were assessed: (a) no window view ("neutral" condition), (b) a side view tangential to the instruction, and (c) direct forward views located behind the instruction area. In both of the window conditions (b and c), the same image of natural exterior scenery was used, consisting of a view of tree-tops and clouds with no motion distractions, buildings, or other human-made elements. Two options for the classroom dimensions were evaluated: (a) narrow classroom of 15 ft by 50 ft, designated as the "neutral" condition, and (b) wide classroom of 22 ft by 50 ft. The ceiling's height was not manipulated in the study; it was held constant at 12 ft in each of the classroom variants. The exact size of the window was not stated. EEG data showed increased oscillatory activity in all recorded channels when exposed to rooms with windows. Although this study did not directly consider stress responses, alpha band power (8–12 Hz) increased when exposed to a room with a greater width, indicating an increased state of relaxation. In sum, the results suggest a potential positive relationship between the windowless and more enclosed spaces and physiological stress levels.

Lastly, to recall, Kim et al. (2021) conducted an EEG study involving 33 female participants who were exposed to VR in private postpartum care rooms. Alongside proportion, the study also investigated the relationship between the degree of enclosure, characterized by the aspect ratio, ceiling height, and window ratio, and RAB activity. Window ratio was determined using the following formula: window area/(exterior envelope wall area + window area) × 100%. Five types of window ratios were defined: 20%, 40%, 60%, 80%, and 100% (discussed in 4.2.3 below). The findings revealed that rooms with higher degrees of enclosure, indicated by lower ceiling heights, smaller window ratios, and length-to-width aspect ratios greater than one, exhibited reduced RAB wave activity. The decrease in the RAB signifies higher stress levels or reduced relaxation states. However, it is essential to acknowledge the complexity in interpreting the study's results due to the interconnected nature of window size, ceiling height, and aspect ratio. Further research is warranted to explore the specific mechanisms underlying these relationships and their implications for creating more comfortable and supportive postpartum care environments.

5 Discussion

The results from the systematic review of the impact of architectural forms on physiological stress responses highlight an important and nuanced relationship between the built environment and human physiology. The findings from this review suggest that certain architectural forms, specifically curvature, enclosure and proportion, may impact physiological stress responses. However, the field of neuroarchitecture is in its infancy, and the techniques for measuring the stress implications of architectural form are still developing. It is evident from the review that there is still considerable scope for further research into human's physiological responses to the built environment. The following discussion highlights a number of critical concerns.

First, there is a limited amount of research examining the impact of architectural form on physiological stress responses. It is noteworthy to acknowledge that the findings pertaining to curvature were not robust, with only one (Shemesh et al., 2021) out of the three scrutinized studies demonstrating a discernible distinction between the impact of curved and linear configurations on physiological stress responses. Furthermore, the studies examining the impact of proportion on physiological stress responses were conducted with a limited sample size, encompassing merely two studies (Kim et al., 2021; Shemesh et al., 2021). While the reviewed studies evidence the potential to measure physiological stress responses to architectural forms using clinical biomarkers, further evidence is needed to substantiate a link between particular architectural forms and physiological stress outcomes.

Second, the precise characterization of curvature, proportion, and enclosure appear to lack uniformity in the reviewed studies. For example, when measuring the effect of curvature on physiological stress responses, Shemesh et al. (2021) defined curvature on a scale from 0 to 4, while Banaei et al. (2017) and Li et al. (2022) defined curvature as a binary (i.e., curved or linear). Moreover, the architectural forms examined in these studies differed greatly, with Shemesh et al. (2021) examining only wall and ceiling curvature while Banaei et al. (2017) and Li et al. (2022) included curvature of archways, and other more decorative features. Similarly, in the studies examining the impact of proportion on physiological stress responses, Kim et al. (2021) altered enclosure by changing space aspect ratio, ceiling height, and window ratio to study their effects on arousal response. In contrast, Shemesh et al. (2022) investigated the emotional impact of narrow spaces (2 m × 4 m × 4 m) compared to wide spaces (6 m × 4 m × 4 m), focusing on proportion as a key architectural element. This inconsistency in definitions or metrics indicates potential variation in interpretive frameworks utilized in these studies, leading to a number of issues. For instance, when measurement terms and criteria are not standardized, it becomes challenging to replicate studies and obtain consistent results. This lack of standardization makes it harder to establish cause-and-effect relationships. Likewise, without standardized metrics, it becomes difficult to compare findings across studies. This hinders the ability to identify trends, patterns, or divergent outcomes, which are crucial for advancing scientific understanding. Going forwards, it would be helpful for future research to actively work toward establishing standardized metrics denoted with consistent terminology.

Third, the reviewed studies examine a variety of settings, including a classroom (Fich et al., 2014; Cruz-Garza et al., 2022) and a postpartum care room (Kim et al., 2021). Some of the reviewed studies examined the impact of the stimuli in isolation and did not consider the context of the environment. For instance, Shemesh et al. (2021) examined the physiological effects of scale, curvature and proportion using multiple clinical biomarkers in a plain white room without any ornamentation, openings (i.e., windows or doors) or contextual indicators (i.e., a bedroom or a work environment). Due to these variations in the settings examined, the findings from one setting may not be transferable to another. For instance, the specific conditions in which an individual experiences certain spaces, such as a postpartum care room, may differ substantially from one another. The context specific nature of the settings thus further limits the ability to generalize the findings of these studies.

Fourth, of reviewed studies, six used virtual reality (Banaei et al., 2017; Kim et al., 2021; Shemesh et al., 2021, 2022; Cruz-Garza et al., 2022; Li et al., 2022) and two of the reviewed studies used 2D visual stimuli (Fich et al., 2014; Vartanian et al., 2015), while only one used physical architecture (Abd-Alhamid et al., 2020). Researchers often use VR and 2D images as proxy stimuli for physical architecture in architectural health research. This allowed the authors to manipulate architectural variables easily. However, it should be noted that VR and 2D images may fail to capture the multisensory nature of physical architecture, and therefore, the transferability of these findings may be limited (Valentine, 2023a). Additionally, VR has been known to induce physiological stress and subsequent distress and discomfort, often referred to as "cybersickness" or "simulator sickness" (Howard and Van Zandt, 2021). The reviewed studies did not control for these variables.

Fifth, the reviewed studies focus only on acute, short term physiological responses and did not consider the long term impacts of exposure to stress inducing architectural forms. However, a recent article has hypothesized that chronic exposure to stress inducing architectural forms may result in allostatic overloading (Valentine, 2023b). Allostatic overloading refers to the chronic or repeated exposure to stress-inducing events which may overwhelm the body's regulatory system, resulting in damage to organs and tissues (Mariotti, 2015). As Valentine (2023b) highlights, future research examining the impact of architectural form on physiological stress responses will need to integrate additional clinical biomarkers, as well as clinimetrics, in order to fully capture the effects of architectural form on human physiology.

6 Conclusion

The results from the systematic review highlight the complex relationship between the built environment and human health, specifically regarding the impact of architectural forms on physiological stress responses. The findings suggest that certain architectural forms, including curvature, enclosure, and proportion, may have the potential to amplify or reduce physiological stress. Additionally, this systematic review underscores the utility of clinical biomarkers in assessing physiological stress reactions to architectural configurations. However, to date, there is a paucity of research on the relationship between physiological stress and architectural form, an absence of uniformity in the metrics engaged to measure and define architectural forms, and a need to account for the contextually distinctive nature of architectural encounters. Moving forward, further research is needed: to standardize the metrics used to define particular architectural forms, to assess the impact of long-term exposure to architectural forms on physiological responses using longitudinal studies, and to produce a more robust body of scholarship on the stress-inducing and reducing impact of architectural forms.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

The author confirms being the sole contributor of this work and has approved it for publication.

Conflict of interest

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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