E-ISSN: 2829-6257
P-ISSN: 2962-5629

Measuring Brain Comfort in Neuro Architectural Research: A Structured Theoretical Review

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Article Info

Article history:

Received April 15th, 2025
Revised June 9th, 2025
Accepted July 17th, 2025

Keywords:

Brain Comfort
Neuroarchitecture Research
Theoretical Study
Neurologist Parameter
Spatial Design

ABSTRACT

Comfort is a central objective in architectural design, yet it varies across individuals. This study proposes an evidence-based framework for assessing comfort through a neuroarchitectural approach by analysing neurological parameters. A meta-analysis of Scopus-indexed literature identified 111 relevant keywords from an initial set of 1,298, derived from 2,561 unique keywords in peer-reviewed studies published over the past decade that employed neurological indicators in neuroarchitecture. The findings indicate that comfort is not solely subjective but can be examined through measurable biological and neurological markers. The literature is organised into three main parameters: environmental simulation and spatial comfort, neurological instrumentation and brain signal processing, and emotional perception and sensory experience. Thematic content analysis and bibliometric mapping were conducted using OpenRefine, VOSviewer, and Biblioshiny. The synthesis reveals clear correlations between neurological responses and architectural elements such as natural lighting, spatial configuration, material texture, and environmental control. These parameters reliably capture the neurophysiological mechanisms underlying comfort in built environments, with perceptual and emotional responses identified as particularly critical. Overall, meta-analysis establishes comfort as an objectively quantifiable phenomenon and provides a foundation for adaptive and inclusive architectural design that supports mental health, cognitive performance, and well-being. Future research directions include experimental studies integrating virtual reality and real-time biometric monitoring to further explore brain–environment interactions.

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1. INTRODUCTION

Architecture is a discipline that relies on creating functional and aesthetically pleasing spaces that cater to human needs, allowing individuals to feel comfortable and engage in activities within these spaces. Comfort in architecture has always been technically linked to the comfort of space, which forms a "sense of comfort" in one's perception. The debate over the perception of psychological comfort is too nuanced to be measured. Often, this psychological comfort is not widely utilised in architectural practice.

The implementation of architectural research is greatly needed in design practice, so architects require a definite measure to ensure that space users feel more comfortable. The main problem in current architectural practice is the lack of a measurable approach that can objectively explain the comfort of space users with clear (not subjective) evidence. This is where the need for a new approach arises, specifically an approach that can interpret comfort based on neurocognitive processes occurring in the human brain. Advances in neuroscience over the last two decades have demonstrated that the perception of space is closely tied to neurological activities in the brain, including emotion regulation, decision-making, and responses to environmental stimuli. This research aims to explore the potential of utilising neuroscience data, including brainwave activity, stress hormones, and neural connectivity patterns, to measure comfort in spatial design. However, the human brain is not a uniform system. Everyone has a different way of processing information, remembering the experience of space, and interpreting comfort. Neurodiverse factors such as age, cognitive background, and certain neurological conditions make measuring comfort a complex challenge.

Thus, the problem this study addresses is how brain comfort can be measured theoretically in architecture, what relevant neuroscience indicators are, and how neuroarchitectural approaches can be formulated systematically to bridge the need for architects for a design based on scientific evidence. Through this approach, comfort is no longer just the result of interpretation but can be traced through objective biological and neurological signals. The results are expected to be the initial and methodological basis for neuroscientific evidence-based architectural research in future architectural design practices.

2. METHOD

This study employed a systematic meta-analytical approach that combined bibliometric techniques and thematic content analysis to investigate neurological parameters related to brain comfort in architectural spaces. Literature was sourced from major academic databases using targeted keywords and filtered through rigorous inclusion criteria focused on empirical studies published within the last 15 years. Data cleaning and keyword standardisation were conducted with OpenRefine, followed by co-occurrence network analysis and clustering using VOSviewer and Biblioshiny software. This multi-stage process enabled mapping thematic patterns and conceptual linkages between neuroscientific measures, spatial stimuli, and user comfort. The method integrated quantitative metadata evaluation with qualitative interpretation to develop a robust, interdisciplinary framework that links neurophysiological responses to architectural design.

2.1. Literature Search Strategy

The literature search for this study was conducted systematically to gather theoretical and empirical findings related to measuring brain comfort within architectural spaces. The search strategy employed specific keywords such as “neuroarchitecture,” “brain comfort,” “EEG and space design,” and “cognitive response to the built environment”. It was carried out through reputable academic databases, particularly Scopus. The keyword “Neuroarchitecture” yielded 317 publications, while “Brain AND Comfort” generated 685 results across six specified subject areas: neuroscience, engineering, psychology, environmental science, multidisciplinary, and arts and humanities, covering the period from 2010 onward. The combination “EEG” AND “space design” returned 14 studies, “Brain” AND “space design” yielded 19, and “Environment” AND “cognitive response” yielded 263 publications. These results were consolidated into a focused dataset using the keywords: "Brain AND Comfort," "EEG AND space design," "Brain AND space design," and "Environment AND cognitive response." They were exported in both .ris and .csv formats for further analysis.

The initial broad search from the Scopus dataset was filtered in the open and refined through predefined inclusion and exclusion criteria. The inclusion criteria were: (1) Publications must be dated within the last 15 years (2009–2024), as visualised in Figure 1. Exceptions were made for earlier works only if they provided essential theoretical foundations. (2) The author's keywords were filtered using OpenRefine to clean and organise data. The filtered data was then analysed using VOSviewer and Biblioshiny. During keyword filtering in VOSviewer, a co-occurrence analysis was applied with a minimum threshold of five occurrences per keyword. From an initial dataset of 2,561 unique keywords, only 111 keywords met the minimum occurrence threshold and were subsequently included in the keyword co-occurrence map for visual analysis. (3) Finally, keyword validation and clustering were performed using Biblioshiny to structure the thematic landscape of the literature corpus.

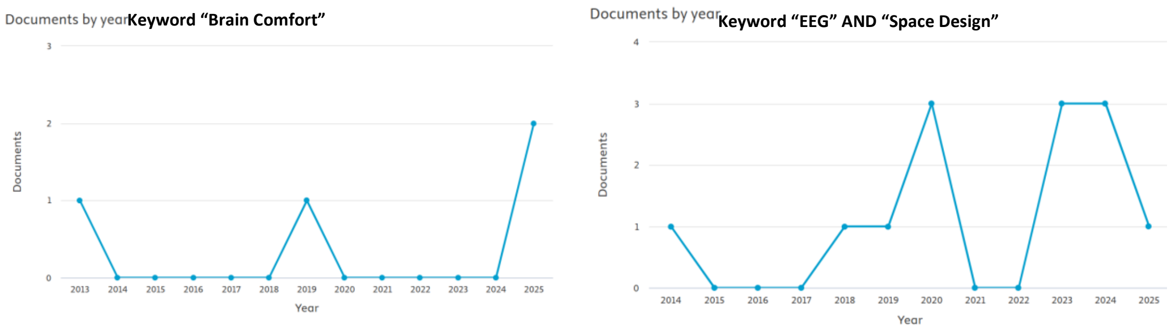

Figure 1. Trend data number of research-on-research data keywords

By identifying at least three keywords that consistently appeared in the co-occurrence analysis, 111 topics were found to have strong keyword strength and thematic significance. To ensure the validity and reliability of the bibliometric study, a Data Quality Check was conducted using the Biblioshiny platform. The evaluation results indicated that most essential metadata fell into the "Excellent" and "Good" categories, confirming that the dataset is valid and suitable for further bibliometric analysis.

Metadata	Description	Missing Counts	Missing %	Status
AB	Abstract	0	0.00	Excellent
DT	Document Type	0	0.00	Excellent
SO	Journal	0	0.00	Excellent
LA	Language	0	0.00	Excellent
TI	Title	0	0.00	Excellent
TC	Total Citation	0	0.00	Excellent
PY	Publication Year	1	0.10	Good
AU	Author	7	0.72	Good
C1	Affiliation	18	1.86	Good
DI	DOI	51	5.26	Good
RP	Corresponding Author	164	16.92	Acceptable
DE	Keywords	165	17.03	Acceptable
ID	Keywords Plus	216	22.29	Poor
CR	Cited References	969	100.00	Completely missing
WC	Science Categories	969	100.00	Completely missing

Figure 2. Data validity according to Biblioshiny

Several key metadata elements, such as Title (TI), Abstract (AB), Document Type (DT), Source (SO), and Language (LA), were found to be 100% complete, with no missing values. These elements were, therefore, categorised as "Excellent." Similarly, other essential fields such as Total Citations (TC), Publication Year (PY), Authors (AU), and Affiliations (C1) had very low levels of missing data (less than 2%) and were classified as "Good."

On the other hand, two metadata components were rated as "Acceptable" due to moderate levels of incompleteness: Corresponding Author (RP) and Author Keywords (DE), which exhibited missing values of 16.92% and 17.03%, respectively. Nonetheless, these values remain within an acceptable threshold for non-quantitative bibliometric analyses. In contrast, two metadata elements, Keywords Plus (ID) and Cited References (CR), showed significantly higher levels of missing data, with 22.29% and 100% missing, respectively. Notably, both Cited References and Science Categories (WC) were completely absent (100%) and thus categorized as "Completely Missing." However, since this study does not focus on citation analysis or disciplinary classification, these gaps do not substantially impact the quality of the keyword and abstract-based thematic analysis. The overall validity of the dataset is considered strong. Most critical variables required for co-word analysis and thematic mapping are available and consistent, thereby supporting the integrity and reliability of the bibliometric process used to explore the concept of brain comfort in this study.

2.2. Meta-analysis using Vos Viewer and Biblioshiny

This study systematically analyses the literature relevant to brain comfort within neuroarchitectural research. The analysis employed a bibliometric approach using VOSviewer software, which generated a visual map of the most frequently occurring keywords and their thematic interconnections. From 2,561 keywords identified across the literature corpus, 111 met the minimum threshold of five occurrences and were subsequently classified into seven main thematic clusters.

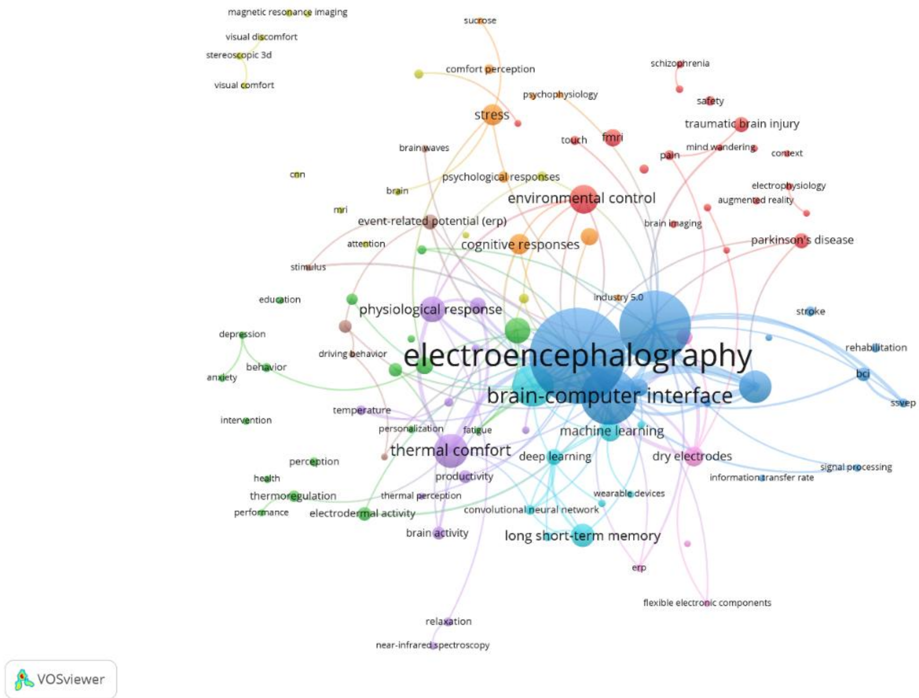

Figure 3. Vos Viewer results of an accuracy analysis map with 10 words that continue to appear in the keyword

Each cluster represents a distinct concentration of issues and scientific approaches that articulate various dimensions of brain comfort measurement, ranging from neurophysiological, cognitive, and perceptual to technological perspectives. This classification provides a comprehensive understanding of the conceptual dimensions underlying the topic of brain comfort. It highlights the close interrelation between diverse scientific approaches spanning neuroscience [1], environmental psychology [2], wearable technology, and architectural design. By integrating these multidisciplinary perspectives, the measurement of brain comfort can be further developed into a more comprehensive and applicable framework for evidence-based spatial design practice.

Table 1. The number of dominant keywords and group keywords with relationships to other keywords

Cluster	Number of Keywords	Full Keywords
Cluster 1 (Neurotechnology and Brain Rehabilitation)	**26**	BCI, brain imaging, brain-computer interface, brain-machine interface, cerebral palsy, dry electrodes, EEG, electrocardiogram, electrodermal activity, electroencephalography, ERP, fatigue, flexible electronic components, functional near-infrared spectroscopy, high frequency steady-state, information transfer rate, intracranial hypertension, mind wandering, P300, personalization, rehabilitation, resting state, signal processing, step, steady-state visual evoked potential, stroke
Cluster 2 (Cognitive and Environmental Performance)	**19**	brain activity, cognitive performance, convolutional neural networks, deep learning, fNIRS, heart rate variability, indoor environment, long short-term memory, machine learning, near-infrared spectroscopy, physiological response, power spectral density, prediction, productivity, relaxation, temperature, thermal comfort, thermal perception, wearable devices

Cluster 3 (Brain Psychology and Comfort)	**16**	brain, comfort, comfort perception, developmental, FMRI, mental health, non-invasive brain stimulation, pain, psychological responses, psychophysiology, restorativeness, safety, stress, sucrose, touch, traumatic brain injury
Cluster 4 (Neuroarchitecture and New Technologies)	**15**	architectural experience, augmented reality, cognitive neuroscience, cognitive responses, context, deep brain stimulation, electrophysiology, emotions, environmental control, industry 5.0, interest literature since 1, intraoperative confusion, neuro-architecture, Parkinson's disease, virtual reality
Cluster 5 (Mental Health and Environmental Perception)	**13**	anxiety, behaviour, cognition, depression, education, eye-tracking, health, intermodulation frequency, intervention, noise, perception, performance, thermoregulation
Cluster 6 (Visual and Sensory)	**8**	attention, CNN, end-state comfort effect, magnetic resonance imaging, MRI, stereoscopic 3d, visual comfort, visual discomfort
Cluster 7 (Stimulus and Emotions)	**6**	brain waves, driving behaviour, emotion, event-related potential (ERP), intelligent connected vehicle, stimulus
No Cluster	**2**	neuroimaging, schizophrenia

2.2.1. Cluster 1 (blue zone) – Neurotechnology and Brain Rehabilitation

The First cluster represents the quantitative and technological dimensions of brain comfort measurement. Dominated by keywords such as electroencephalography (EEG), brain-computer interface (BCI), dry electrodes, and signal processing, it highlights the critical role of objective tools in detecting and quantifying the brain's responses to the built environment. In neuroarchitecture, EEG and other neurophysiological technologies serve as primary indicators for identifying real-time brain activity as individuals interact with spatial environments [3]. Applications in rehabilitation and brain monitoring further extend the relevance of brain comfort assessment to vulnerable populations, such as individuals with stroke or cerebral palsy [4]. The topics within this domain provide objective biometric data [5], offering neurological evidence that supports evaluating spatial design through the lens of brain comfort.

2.2.2. Cluster 2 (purple zone) – Cognitive and Environmental Performance

The Second cluster integrates environmental factors such as [6], temperature [7] and [3] indoor environmental quality [8] with cognitive performance indicators [9], including brain activity, relaxation, and productivity. The emphasis on wearable devices, physiological responses, and machine learning reflects a technologically adaptive approach to measurement. It illustrates ongoing efforts to link the quality of physical environments such as temperature, lighting, and acoustic comfort with brain performance, particularly within the context of workplace [10], educational [11], and public facility design [12]. This cluster serves as a bridge for quantitatively assessing the impact of environmental conditions on brain function and performance, thereby contributing to the measurement of brain comfort.

2.2.3. Cluster 3 Red Zone – Psychology and Brain Comfort

The third cluster emphasises the affective and perceptual dimensions of brain comfort. Keywords such as comfort perception [13], [14], stress [15], psychological responses [16], and mental health [17] underscore the importance of the subjective construction of comfort, which cannot always be captured through physiological measures alone. In neuroarchitectural research, brain comfort is not solely the product of neurological signals but also shaped by users' cognition and subjective perception of space. This cluster provides a critical foundation for integrating quantitative and qualitative comfort assessment approaches [18]. It highlights that brain comfort is influenced by subjective perception and emotional balance, underscoring the need for holistic methods in measuring cognitive well-being within designed environments.

2.2.4. Cluster 4 Orange Zone – Neuroarchitecture and New Technologies

The fourth cluster reinforces the integration of neuroscience, architectural experience, and emerging technologies. Keywords such as architectural experience, virtual reality, neuroarchitecture, and cognitive neuroscience focus on exploring spatial brain experiences through simulated and experimental approaches. Virtual reality (VR) and augmented reality technologies offer new opportunities to measure brain responses to space in a controlled and flexible manner, paving the way for innovative methods in brain-based spatial comfort assessment [19]. This cluster introduces simulation-based experimental methodologies and predictive design strategies through technology, advancing the measurement of brain comfort.

2.2.5. Cluster 5 Green Zones – Mental Health and Environmental Perception

The fifth cluster emphasises the significance of spatial design in promoting mental health. Keywords such as anxiety, depression, noise, cognition, and perception indicate that environmental conditions significantly influence an individual's psychological state, ultimately affecting brain comfort. This connection reinforces the notion that space is not neutral. It can either trigger psychological distress or help alleviate it through a design attentive to perception and sensory stimuli [20]. This topic provides critical context for understanding the role of the built environment in shaping users' emotional and neuropsychological balance, contributing to a more comprehensive measurement of brain comfort.

2.2.6. Yellow Zone Cluster 6 – Visual and Sensory

The sixth cluster highlights the importance of visual stimuli and sensory comfort in shaping perceptions of brain comfort. Keywords such as visual comfort, MRI, and stereoscopic 3D emphasise that the design of lighting, colour, and visual form significantly influences spatial and cognitive perception. Advanced visual technologies such as fMRI and convolutional neural networks (CNN) reflect emerging explorations into the correlation between visual design and brain activity. Visual and sensory stimulation directly regulate perception and promote brain relaxation, underscoring the critical impact of visual quality in assessing brain comfort.

Table 2. Clustering based on dominant keywords and the use of methods with Brain Comfort measurement

Cluster	Main Topic	Dominant Keyword	Measurement, Method / Indicator	Contribution to Brain Comfort
Cluster 1 (Blue zone)	Neurotechnology and Brain Rehabilitation	electroencephalography, brain-computer interface, dry electrodes, stroke, EEG	EEG, BCI, dry electrodes, P300, SSVEP, ERPs	Provide objective neurological data to measure brain activity in response to space
Cluster 2 (Purple zone)	Cognitive and Environmental Performance	brain activity, thermal comfort, productivity, wearable devices	Thermoregulation sensors, EEG, HRV, fnIRS	Linking environmental factors (temperature, comfort) to brain efficiency and function
Cluster 3 (Red zone)	Brain Psychology and Comfort	comfort perception, psychological responses, stress, pain, mental health	Questinaire, stress scale, hormon (cortisol), fMRI	Mapping affective and perceptual responses to space as dimensions of comfort
Cluster 4 (Opens zone)	Neuroarchitecture and New Technologies	architectural experience, neuro-architecture, augmented reality, virtual reality	VR/AR simulation, cognitive task-based testing	Testing the impact of space design through virtual simulations and experimentation
Cluster 5 (Green zone)	Mental Health and Environmental Perception	anxiety, noise, cognition, depression, perception	Psychometrics, Noise level measurement, eye-tracking	Explain the influence of the environment on mental health and spatial perception
Cluster 6 (Yellow zone)	Visual and Sensory	visual comfort, MRI, stereoscopic 3D, attention	fMRI, visual ERP, stereoscopic stimulus	Evaluating the effects of visual stimuli on the sensory system and brain comfort
Cluster 7 (Grey zone)	Stimulus and Emotions	brain waves, emotion, stimulus, driving behaviour	EEG, ERPs, stimulus-response testing	Trace the relationship between direct stimuli and emotional changes or brain waves.

2.2.7. Cluster 7 Grey Zone – Stimulus and Emotions

The last cluster integrates the relationship between direct environmental stimuli such as light, sound, and motion and emotional and behavioural responses. Terms such as brain waves, emotions, and event-related potentials reflect the brain's rapid reactions to stimuli within interactive contexts [21]. In neuroarchitecture, this approach can measure how micro-interactions with spatial elements (e.g., door sounds, temperature shifts) trigger or alleviate brain stress. Its contribution to measuring brain comfort highlights the significance of micro-stimuli sensitivity and the brain's immediate responses to surrounding environments [22].

In addition to the seven main clusters, two keywords, neuroimaging [23] and schizophrenia [24], emerge as independent topics, not strongly connected through co-occurrence networks. Despite their lack of clustering, both contribute significantly to the discourse on brain comfort. Neuroimaging is an objective measurement method that visualises the brain's responses to spatial stimuli, utilising fMRI or PET scans. This technology reinforces the biological validation of neuroarchitectural studies. Schizophrenia, on the other hand, reflects attention toward neurodivergent populations, indicating that spatial design can influence the perceptual and cognitive stability of individuals with mental health conditions. Together, these topics extend the scope of brain comfort into clinical and experimental domains, enriching the conceptual framework for measuring cognitive and emotional well-being in architectural contexts.

2.3. Analysis Techniques

The analytical process in this study employed an exploratory bibliometric approach supported by the Bibliometrix software (via Biblioshiny) and VOSviewer, with the aim of mapping trends, thematic connections, and the conceptual framework of literature related to brain comfort in the context of neuroarchitecture. The analysis was conducted through the following stages:

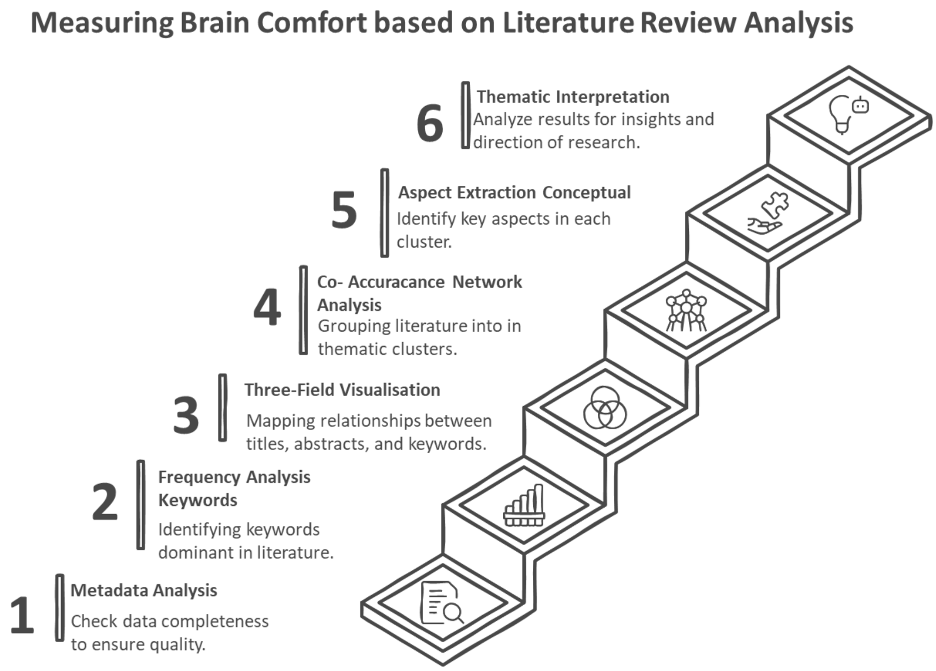

Figure 4. Meta-analysis methods used in the study

1. Metadata Analysis: The initial phase involved a data quality check of metadata, including titles, abstracts, publication years, keywords, affiliations, and DOIs. The validation results indicated that most of the metadata fell within the "Excellent" and "Good" categories, confirming its reliability for further analysis.
2. Keyword Frequency and Distribution Analysis: The dataset was then examined to identify the most frequently occurring keywords across titles, abstracts, and author-provided keyword lists. This step provided an initial overview of dominant thematic terms within the literature.
3. Three-Field Plot Visualisation: This visualisation technique was used to map the relationship between three core elements: title terms (TI_TM), abstract terms (AB_TM), and merged keywords (Kw_merged). It helped identify conceptual linkages and terminological consistency that underpin the central theme of brain comfort.

4. Co-Word Network Analysis: Using VOSviewer, a co-occurrence analysis of keywords was conducted to cluster the literature into thematically related groups. Each cluster represented a specific area of inquiry, such as neurotechnology, environmental psychology, visual comfort, or experimental technology.
5. Conceptual Aspect Extraction: From each identified cluster, three primary aspects were extracted: (1) types of neurological responses, (2) instruments or measurement tools used, and (3) architectural or environmental stimuli. This approach enabled the development of a conceptual map linking neuroscientific data with spatial design principles.
6. Thematic Interpretation: The resulting visualizations and clusters were analysed qualitatively and descriptively to identify research trends, existing gaps, and potential theoretical frameworks supporting brain comfort measurement within neuroscience-based design.

These techniques provide a robust foundation for constructing a thematic map and conceptual structure of brain comfort as an interdisciplinary approach that integrates architectural design, neuroscience, and environmental psychology.

3. RESULT AND DISCUSSION

3.1. Meta-Analysis Results using Biblioshiny

The advanced analysis employed a Three-Field Plot visualization to map the interconnections among three key components of scientific publication structures: article titles (TI_TM), abstracts (AB_TM), and merged keywords (KW_Merged). The primary objective of this analysis was to identify thematic consistency and to trace the relationships among core terms that underpin the focus of the literature on brain comfort within the context of neuroarchitecture.

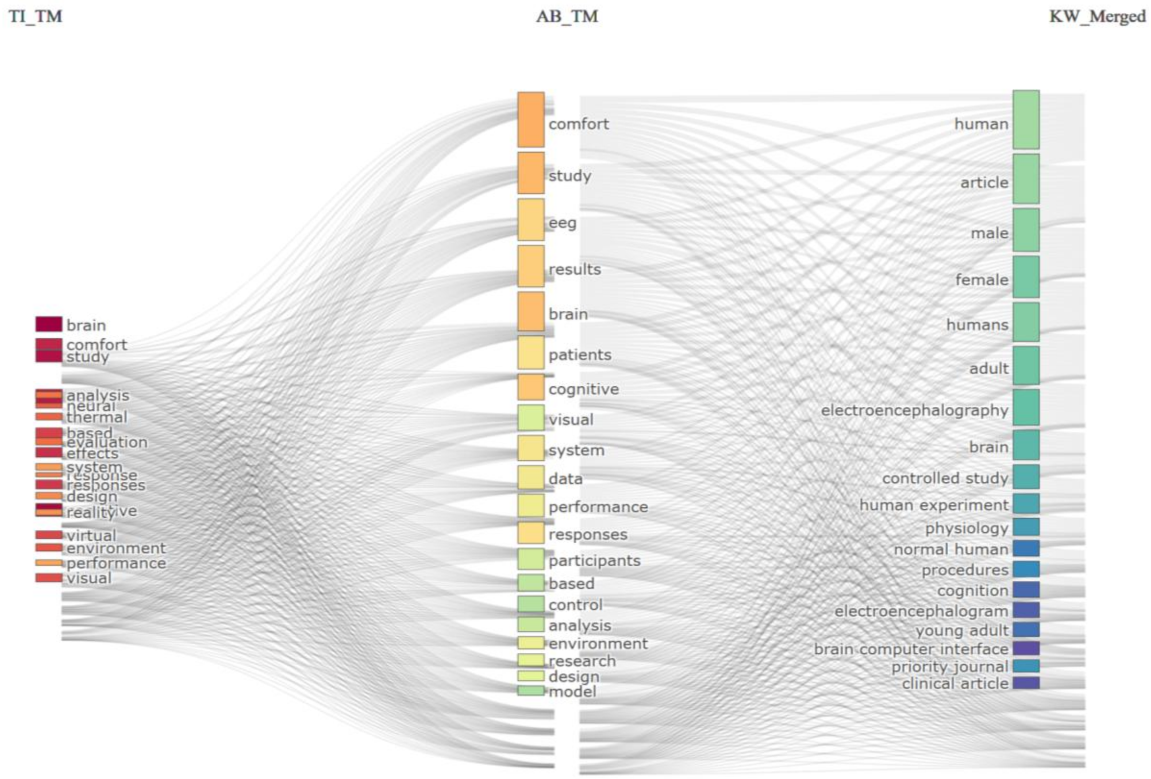

Figure 5. The results of frequency analysis using three free plots by looking at the coherence of titles, abstract content and keywords

The ten most dominant terms in the article title column are brain, comfort, study, analysis, neural, thermal, visual, performance, environment, and design. These keywords indicate that the analysed studies generally focus on the interrelationship between brain comfort, cognitive performance, and environmental factors such as temperature and the visual qualities of space, approached through quantitative and systems-based methods. Meanwhile, terms like comfort, study, EEG, results, brain, patients, cognitive, visual, and performance consistently appear in the abstract column. This suggests that abstracts reiterate the keywords from the titles and clarify the study populations (e.g., patients) and the neurological measurement methods employed, particularly electroencephalography (EEG). The focus reflects an experimental [25], outcome-oriented approach to understanding brain responses within built environments. In the merged keyword column (KW_Merged), authors' most frequently used terms include human, electroencephalography, controlled study, brain, human experiment, physiology, cognition, and brain-computer interface. This coherent result confirms that most literature relies on direct brain measurements via EEG or brain-computer interface (BCI) within controlled studies involving adult human subjects [26].

The three-field Plot reveals a strong thematic cohesion among the terms used in titles, abstracts, and keywords. Comfort, brain, and EEG appear consistently across all three fields, indicating that brain comfort is a central theme that can be measured neurologically through human-based experimental design. This visualisation further reinforces that approaches to measuring brain comfort are quantitative, physiology-based, and aimed at directly responding to spatial elements, such as visual environment, thermal comfort, and spatial design. The findings from the Three-Field Plot demonstrate strong thematic cohesion across titles, abstracts, and keywords. The consistent presence of terms such as comfort, brain, and EEG signifies that brain comfort holds a pivotal position in literature. Generally, the analysed studies employ experimental, human-subject approaches using neurological measurements, such as EEG to evaluate brain responses to environmental design elements. These findings strengthen the understanding that brain comfort measurement is quantitative and physiological-driven, targeting direct reactions to environmental stimuli such as lighting, colour, shape, temperature, and sound. Within this context, brain comfort can be defined as a condition where physical environmental design elements—such as light, colour, form, sound, and texture—elicit neurological responses that promote emotional balance, concentration, and relaxation. The ultimate goal is to create aesthetically pleasing spaces that align with human biological and psychological needs, thereby contributing to overall enhanced comfort.

Two complementary visualisation approaches were employed to reinforce the meta-analysis results and literature classification: the Three-Field Plot and thematic analysis based on dendrogram clustering. The Three-Field Plot illustrated terminological consistency across titles, abstracts, and keywords, highlighting strong thematic cohesion around comfort, brain, and EEG. This underscores brain comfort as a primary focus in recent studies, emphasising neurologically based experimental measurement approaches involving human subjects. Subsequently, a thematic analysis was conducted using factorial methods and visualised through hierarchical dendrograms to deepen the conceptual mapping of the literature. Unlike the Three-Field Plot, which emphasises term continuity, the dendrograms reveal how related keywords cluster into more specific thematic groups. These clusters represent diverse methodological orientations and thematic foci, including EEG technology, virtual simulation, visual perception, thermal comfort, and clinical studies involving human participants. Together, these two visualisation methods provide a more comprehensive picture of the evolving concept of brain comfort in neuroarchitecture, tracing its development in terms of terminology, methodological approaches, and underlying conceptual frameworks.

Figure 6 below illustrates the thematic analysis results using a factorial approach, visualised as a hierarchical dendrogram. This analysis groups keywords based on their co-occurrence and thematic relatedness, aiming to identify the conceptual structure within the literature addressing brain comfort. Each branch of the dendrogram represents a cluster of keywords that frequently appear together and share semantic proximity across scientific articles. The distance between nodes reflects conceptual distance: the closer two terms are, the more often they co-occur and the higher their thematic relevance. Firstly, an independent cluster emerges linking the topics of virtual reality and thermal comfort, indicating scholarly attention to spatial simulation and the influence of temperature on brain comfort. Secondly, a dense cluster includes terms such as EEG, electroencephalography, electrodes, and brain-computer interface, underscoring the dominance of brain activity recording methods in measuring brain comfort. Other clusters reveal associations between terms like perception, emotion, visual stimulation, and comfort, highlighting that emotional responses and visual perception are integral components of the neuroarchitectural approach. At the lower part of the dendrogram, keywords are grouped, including human, young adult, patient comfort, and controlled study, illustrating that most studies employ experimental designs involving human subjects in clinical settings and laboratory simulations.

Figure 6. The results of the thematic analysis with the evolution of the theme using the factorial method

These results reinforce that brain comfort in scientific literature is not merely a theoretical concept, but also a measurable phenomenon, as demonstrated through quantitative approaches based on brain technology and spatial perception. The dendrogram illustrates a consistent conceptual structure that links physiological aspects, technological methods, sensory experiences, and environmental design. This supports three core aspects emerging from the three clustered groups identified in the thematic analysis, which map the relational patterns in brain comfort measurement. Together, they establish associations between architectural design elements and human neurological responses. Each relevant article or study was analysed to identify the types of brain responses observed, the measurement instruments employed, and the architectural elements acting as stimuli.

3.2. A growing literature with Neurological Parameters to explain Space Comfort

Thus, the results of this meta-analysis emphasise that brain comfort is not merely a subjective interpretation but can be objectively explained and validated through measurable neurological parameters. The six main categories identified indicate an increasingly concrete direction in developing neuroscience-based design, with direct contributions to creating adaptive, inclusive spaces that optimally support human brain function. These findings bridge the gap between neural perception theory in architecture and its practical implementation in spatial design. The following Table 3 presents a summary of these results:

Table 3. The main parameter group for measuring architectural comfort.

No.	Cluster Theme	Representative Keywords	Type of Brain Response Observed	Measurement Tools	Architectural Stimuli	Representative Research
1	Environmental Simulation & Spatial Comfort	virtual reality, thermal comfort, environmental control	Thermoregulatory and spatial adaptation responses	VR simulation tools, environmental sensors	Temperature, spatial layout, immersive environment	[27].; [7]; [28]; [19]; [29];[30]; [31]; [32];[33];
2	Neurological Instrumentation & Brain Signal Processing	EEG, electroencephalography, electrodes, brain-computer interface	Cortical activity patterns, brainwave fluctuations	EEG, ERP, BCI, dry electrodes, signal processing tools	Ceiling height, lighting geometry, spatial openness	[34];[35]; [36];[37];[38]
3	Emotional Perception & Sensory Experience	perception, emotion, visual stimulation, comfort	Affective responses, emotional regulation, sensory integration	fMRI, eye-tracking, subjective comfort scales	Colour, texture, lighting intensity, visual scenes	[39];[40]; [41]; [42]; [43]

The meta-analysis reveals that brain comfort within neuroarchitecture can be conceptualised through three interrelated dimensions: environmental simulation and spatial comfort, neurological instrumentation and brain signal processing, and emotional perception and sensory experience. Firstly, ecological simulation employs virtual reality and precise environmental controls to replicate thermal and spatial conditions that elicit thermoregulatory [44] and spatial adaptation [45] responses in the brain. Secondly, neurological approaches predominantly utilise tools such as EEG and brain-computer interfaces to observe cortical activity patterns [46] and brainwave fluctuations [47], serving as objective indicators of brain comfort influenced by architectural elements like lighting geometry and spatial openness. Thirdly, emotional and sensory perception significantly contributes to brain comfort, where visual stimuli such as colour and texture trigger affective responses measurable through fMRI, eye-tracking, and subjective comfort scales. Together, these dimensions demonstrate that brain comfort transcends subjective interpretation and can be objectively quantified through neurophysiological responses directly shaped by physical environmental design. This integrative understanding provides a robust foundation for developing adaptive, inclusive, and optimised spaces that support human brain function and well-being.

About previous studies, this research affirms and extends the discourse on neuroarchitecture. For instance, prior work by Coburn et al. and Bail has emphasised the influence of spatial configurations and environmental stimuli on emotional regulation and cognitive load [48]; [49]. Similarly, recent advancements in EEG-based studies have demonstrated that fluctuations in alpha and theta wave patterns are correlated with perceived spatial comfort and relaxation [50]. Additionally, studies utilising immersive VR simulations have confirmed the utility of environmental emulation in capturing real-time neurological responses to architectural elements [21]. However, unlike earlier studies that often focus on isolated parameters or experimental conditions, this study integrates diverse sources and methods to build a comprehensive metaframework. It identifies dominant neurological indicators and clarifies their interrelations and implications for design decision-making in architectural contexts.

This study successfully delineates the theoretical foundations of brain comfort by integrating insights from the nervous system, sensory perception, and cognitive-affective brain functions. Based on a filtered dataset of peer-reviewed literature, the meta-analysis identifies and validates three key neurological parameters, spatial perception, emotional-affective response, and brainwave activity, as reliable indicators for assessing comfort in architectural contexts. The study uses a bibliometric approach and thematic synthesis to present a current scientific mapping of the neuroarchitectural discourse. It proposes a conceptual framework for spatial design that aligns with users' neurophysiological and psychological well-being. This integrated contribution strengthens the position of neuroarchitecture as an evidence-based discipline, encouraging further interdisciplinary research in creating responsive environments that respect and enhance brain-based human experiences.

4. CONCLUSION

This study was initially designed to explore and validate various neurological parameters used in neuroarchitecture research, as outlined in the introductory chapter. The primary objective was to establish a valid, scientifically evidence-based mapping of how spatial elements influence the human neurological system. This goal was achieved through a systematic meta-analysis of 50 carefully selected studies, as detailed in the Results and Discussion chapter, where all six key neurological parameters were rigorously analysed and validated against existing empirical evidence.

The findings demonstrate a strong alignment between the research objectives and the results obtained. Specifically, brainwave activity (notably alpha and theta rhythms), stress biomarkers such as cortisol, and indicators of spatial perception and emotional response emerged as highly reliable measures of human interaction with the built environment. Moreover, a consistent relationship was identified between architectural design elements- natural lighting, vegetation, texture, and spatial configuration—and users' neurophysiological responses. These insights highlight the potential for integrating neurocognitive considerations into spatial design to improve mental health, comfort, and cognitive performance.

The implications for future application and development are significant, particularly in creating more inclusive and adaptive environments grounded in neurocognitive metrics. Potential applications include residential spaces, educational institutions, healthcare facilities, and workplaces that promote recovery, focus, and healthy social interaction. Additionally, this research opens up avenues for real-time, physiology-driven design models that employ EEG and other biometric technologies.

Looking ahead, advancing neuroarchitecture research through field experiments involving direct human engagement in real-world settings will be critical. Integrating emerging digital tools such as virtual reality (VR) modelling and biometric tracking promises to deepen our understanding of brain-space interactions with greater precision. Overall, this study provides a robust foundation for the practical and sustainable advancement of neuroarchitecture as an interdisciplinary field.

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