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Learning from neuroscience: integrating users in design processes using brain imaging tools and virtual reality

Fatemeh Taherysayah[a,b], Claudia Westermann[a] and Hai-Ning Liang[c]

[a]Department of Architecture, Xi'an Jiaotong-Liverpool University, Suzhou, People's Republic of China; [b]School of Architecture, University of Liverpool, Liverpool, UK; [c]Computation Media and Arts Thrust, The Hong Kong University of Science and Technology (Guangzhou), Guangzhou, People's Republic of China

ABSTRACT

Historically, the close-knit relationship between design and construction ensured that built architecture harmonised with its local context and users, as it originated from the shared experiences of a community. However, with the establishment of architecture as a discipline taught at universities, users and their needs have been deemphasised in the design process. Addressing the challenges of user-centred design, this paper reports on insights from a five-year research project focused on integrating user experiences during the design process. Specifically, as a review of existing research revealed novel opportunities for empirical research on users' experiences in designed environments via brain imaging tools, electroencephalography (EEG) in particular, and virtual reality (VR), our research conducted in several phases tested the integration of these technologies. Our research fills a gap, as despite growing interest in employing EEG and VR in architectural research, a comprehensive strategy for their integration into the design process has not been formulated. An initial review of existing design process models, which do not integrate real-time user experience, nevertheless assisted us in identifying potential stages for such integration. Building upon insights from research experiments, we propose a new design process model that builds the foundation for a comprehensive user-centred neuro-architectural design methodology.

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Design process; virtual reality (VR); electroencephalography (EEG); user-centred design; aesthetic experience

1. Introduction

Since antiquity, construction and planning have been intricately integrated, whether in vernacular architecture in mostly rural contexts or in urban contexts, often involving a master builder who oversees the planning process (Burr and Jones 2010, 122). Architects of the past maintained a direct and intimate connection with the users of the spaces they designed, collaborating with skilled artisans and builders (Hewitt 2020, 243–246). A historical shift occurred during the 14th to 18th centuries, when guilds lost prominence and universities took on a central role in architectural education (Archer 1979, 18).

Since the invention of architecture as an academic discipline in the seventeenth century (Kostof 1995, 527), the architectural design process has changed significantly, leading to the neglect or marginalisation of user needs and desires (Norberg-Schulz 1980). Being separated from the site, architects found it challenging to identify the specific needs of individual users; they had to cater to the average needs of the typical end user (Friedman 1972, 45). This transformation starkly contrasts with insights from recent neuroscience

CONTACT Fatemeh Taherysayah F.taherysayah19@student.xjtlu.edu.cn, F.taherysayah@liverpool.ac.uk Department of Architecture, Xi'an Jiaotong-Liverpool University, DB423, XJTLU south campus, 8 Chongwen Road, Suzhou Industrial Park, Suzhou, Jiangsu Province 215123, People's Republic of China

research that environments impact humans in their well-being to a much larger extent than previously believed (Gage 2003; Gage 2009).

Recent findings in cognitive neuroscience have demonstrated that environments have a cumulative impact on gene function (Eberhard 2015). Alterations in the environment could modify the structural and biochemical composition of the brain, subsequently leading to changes in our behaviour (Gage 2003; Gallese 2017, 195). The discovery of *neuroplasticity*[1] and the *mirror mechanism*[2] has revealed novel insights into the body-environment relationship (Eberhard 2009, 65; Gallese 2015, 87; Gage 2003; Mallgrave 2015b, 17).

Recognising the significance of reintegrating humans into the core of architectural design practice, several endeavours have been conducted aiming to consider users and their needs throughout the design process in the modern era (Cross 1971; Fathy 2010; Friedman 1972, 45). While user-centred design (Norman 2013, 1988) and participatory design (Cross 1971) have suggested methodologies for the reintegration of human users into the core of design (Friedman 1972, 45; Luck 2018, 140), they have faced challenges in practice, such as the lack of a common language or vocabulary, particularly in specialised cases (Luck 2003). Additionally, users often face challenges in articulating their needs regarding buildings or discussing their needs and desires (Fathy 2010).

In this context, environmental psychology, as a partnership between architecture and psychology formed at the end of the 1960$_s$ (Flade 2021, 1), has made valuable contributions to exploring the mutual relationship between humans and their environment. However, studies show that consciously given responses through behavioural tests are often self-censored or manipulated, potentially contaminating the collected data (Ramachandran and Hirstein 1999, 32). Therefore, while acknowledging the significance of behavioural studies, a complementary approach is needed to assess the experiences of individuals in their environments.

To effectively tackle these challenges and successfully integrate human users into the design process, two fundamental questions must be addressed: (RQ1) Which methods can effectively assist us in collecting users' responses and reflections on the environment? and (RQ2) Which stages of the design process can potentially incorporate user input?

To respond to the first question, we conducted an initial review of existing research, tools and methods. It revealed that recent advances in cognitive neuroscience technology have introduced brain imaging methods that provide new possibilities to gather real-time data on how environments impact user experiences in a variety of contexts (Norwood et al. 2019, 10). Based on these insights, we focused on conducting further tests related to the suitability of employing brain imaging tools and related methods for analysis to evaluate users' experiences within designed environments.

Brain imaging methods were developed during the twentieth century (Haas 2003) and encompass a wide range of tools and processes. EEG distinguishes itself by its ability to record context-related signals, provide millisecond-level temporal resolution – allowing researchers to monitor rapid changes in neural signals in real-time – and offer an immediate reflection of postsynaptic changes (Bell and Cuevas 2012, 281; Lau-Zhu, Lau, and McLoughlin 2019, 2). Recent portable EEG devices, recognised for their mobility and affordability, offer potential for incorporation into routine design practices.

To assess the suitability of electroencephalography (EEG) to evaluate users' experiences within the representation of designed projects in virtual environments, we conducted an experimental study, with a summary of its implementation and findings presented in Section 2. Our empirical research has shown that recent approaches in neuroarchitecture are well suited to complement existing methods in environmental psychology.

Addressing the second question, this paper presents an assessment of several important design process models and examines how users are involved in each. Additionally, it pinpoints design process stages suitable for further integration of human experience presented in Section 3. Building upon the findings from the experimental study and the assessment of existing design models, we developed a new preliminary design model that incorporates EEG and virtual reality (VR) to integrate users' experiences into the design process, as outlined in Section 4. Finally, this article outlines a set of strategies as guiding principles for architects seeking to effectively integrate user experience into their design processes.

2. Exploring the suitability of EEG to collect user feedback during the design process

2.1. Methodology

In response to the first question presented in the introduction regarding which methods can effectively assist in collecting users' responses and reflections on the environment, this study conducted an experiment

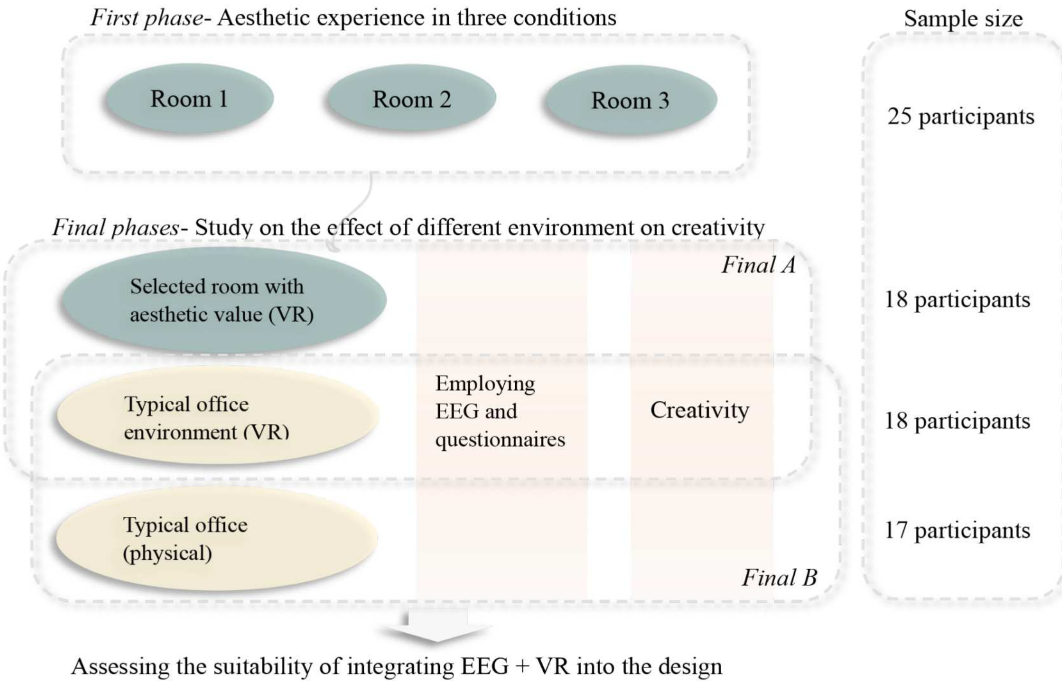

Figure 1. The stages of the experimental phase of this study.

structured into three phases to investigate the suitability of utilising EEG and VR within the design process (Figure 1). This experiment was designed based on an extensive and systematic review of existing empirical studies that use brain imaging tools in virtual and/or physical spaces, conducted by our research team and already published (Taherysayah et al. 2024). This review found that there is a need to develop strategies for integrating EEG data into the architectural design process. It also indicated that research on the environmental impact on humans has primarily focused on fundamental cognitive processes, such as memory and attention. However, a broader range of cognitive activities, such as those related to creativity, has not been adequately studied in this context.

Therefore, this experiment focuses on creative performance in spaces of high aesthetic quality, comparing EEG data from both VR and physical spaces to data obtained from standard creativity questionnaires and tasks. In addition, we decided to focus on aesthetic experiences as context for the experiments due to their role in shifting attention, broadening perspectives, and stabilising the human-environment relationship (Pask 1971, 1975; Westermann 2019, 240–242).

This experiment used a mixed-methods approach, incorporating qualitative methods such as a drawing test and an open-ended questionnaire, as well as quantitative techniques like EEG and questionnaires like Positive and Negative Affect Schedule (PANAS), Short Stress State Questionnaire (SSSQ) and Flow State Scale (FSS). Throughout the experiment, while participants were experiencing physical and VR spaces, their brain waves were recorded employing the 32-channel Emotive EPOC flex EEG, using conductive gel. The protocol followed in all phases of this experiment strictly complied with the guidelines approved by the Ethics Committee of Xi'an Jiaotong-Liverpool University and was consistent with the approved research proposal RDF-18-01-35.

2.2. Participants and materials

The first phase involved 25 participants from a design school, comprising 13 undergraduate students as novice designers and 12 faculty members as expert designers. This phase explored the aesthetic experience of the participants under three different conditions in VR. The rooms recreated in VR for this phase mimicked the famous art installations *Infinity Rooms* by Yayoi Kusama and *Breathing Light* by James Turrell, which have been displayed for many years and have been widely discussed for their spatial impact and aesthetic quality.

Additionally, a design that won first prize in the *Architecture Futures* competition (Westermann 2021) *From 5000 Bricks to 5000 things* by Shiqi Deng, was given as another option (Figure 2). In this experiment, the room designed to mimic Kusama's installation is referred to as *Room Dots VR*, the space crafted to mimic Turrell's installation is denoted as *Room Blue VR* and Deng's creation is named *Room Toy VR*.

In the *second* (*Final) phase A*, 18 participants engaged in creative tasks within the environment selected in the *First phase,* while another 18 participated in a VR office space with moderate aesthetic quality. This phase utilised three creative tasks including the Word Association Test (WAT), a VR drawing and the Alternate Uses Test (AUT). The aim was to assess participants' creative performance under different conditions using EEG, psychological tests, and creativity tasks. In addition, during the second (final) phase B, we compared a physical office space with its VR representation by having 17 participants perform creative tasks in the actual physical office environment (Figure 2). The experimental process timeline is illustrated in Figure 3.

2.3. Data analysis

During EEG data preprocessing, independent component analysis (ICA) and bandpass filtering were applied in the range of 1–45 Hz. Subsequently, frequency band power was extracted for the sub-bands of theta (4-8 Hz), alpha (8-13 Hz), beta (13-30 Hz), and gamma (30-40 Hz) from all 32 channels. The analysis involved two sets of tests conducted using SPSS. The first set focused on identifying significant differences in frequency band power across various conditions. The second set examined potential correlations between frequency band power and aesthetic appeal ratings from the first phase, as well as creativity scores from the second phase. All *p*-values obtained from pairwise comparisons of frequency band powers, using the Wilcoxon Signed Ranks Test in the first phase and the Kruskal–Wallis Test in the second phase, were presented in separate tables for each brain region, including frontal, temporal, parietal, and occipital lobes. In addition, visualisation methods like *heat maps* were employed for further analysis.[3]

2.4. Results of the experiment

This experiment, measuring participants' brain responses with EEG, indicates differences in their experience in rooms with varying levels of aesthetic quality. Comparing the participants' brain activity in three different

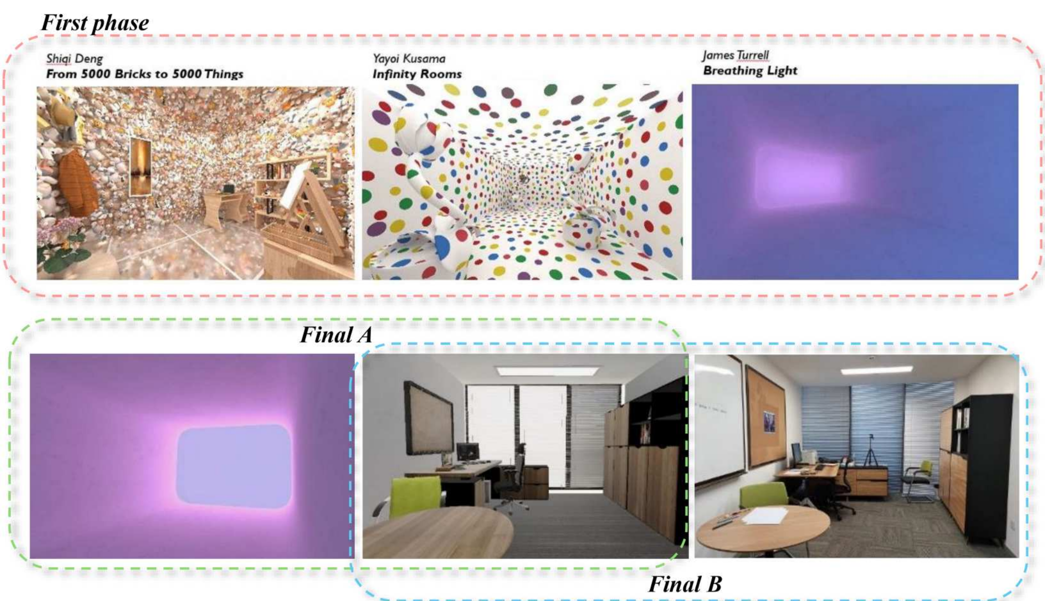

Figure 2. Top: Environments with aesthetic quality for the first phase of the experiment. Down: Environments including a room with an aesthetic environment selected in the first phase and a typical office space in both VR and physical conditions.

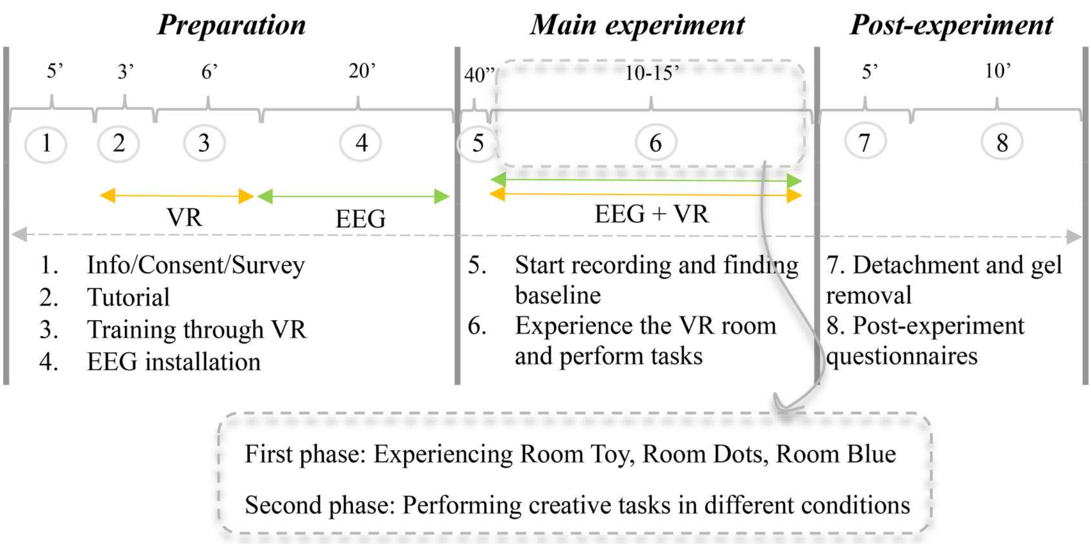

Figure 3. Experimental process timeline.

rooms showed significantly higher occipital gamma in *Room Toy VR* due to the higher cognitive processing demands (Barr et al. 2009, 2359), including aspects of perception, attention (Müller, Gruber, and Keil 2000, 283), memory (Lin, Shu, and Singh 2023, 3), and focused attention (Doyle 2016, 38) required to recognise the numerous objects and details in this room. However, *Room Blue VR* exhibited higher frontal alpha, which is associated with relaxed conditions (Srinivasan and Nunez 2017) and higher aesthetic perception (Cheung, Law, and Yip 2015, 14; Chew, Teo, and Mountstephens 2016, 172). In addition, *Room Blue VR* showed a robust frontal and occipital network of theta power from frontal to occipital, indicating a connection between executive function and visuospatial attention (Kao, Huang, and Hung 2013, 475), contributing to the suppression of distracting and irrelevant visual information (Asanowicz et al. 2023, 1996).

Additionally, a negative correlation was observed between the right frontal beta and gamma activity and the aesthetic appeal rating, leading to the hypothesis that participants may be more likely to rate the room as appealing as the levels of right frontal beta and gamma decrease. Findings revealed differences in brain patterns, both in distribution and amplitude, among three different conditions. Furthermore, the participants' creativity scores were slightly higher in Room Blue VR, a space with high aesthetic quality, than in the VR office room. Considering that Room Blue VR was not primarily designed for creative tasks but nevertheless scored equal to higher than the office space designed for this purpose brings forth valuable insights.

Regarding the comparability of a physical room and its VR representation, despite some differences, the presence of similar patterns in heat maps and brain maps, along with comparable creative scores, slightly higher for the physical condition, and analogous psychological reflections, confirms that virtual representations hold significant promise as alternatives for studying the impact of designed projects on cognitive and creative activities using brain imaging methods. This finding is consistent with existing studies, such as those by Kalantari et al. on cognitive tests (Kalantari et al. 2021), Marín-Morales et al. on arousal and valence (Marín-Morales et al. 2019), and Vaquero-Blasco et al. on stress relief (Vaquero-Blasco et al. 2020), demonstrating the comparability between VR and physical conditions in specific domains.

Therefore, this experiment demonstrated the significant potential of EEG in revealing differences in human response and reflection under various conditions, whereas questionnaires showed fewer distinctions. The study concludes that the combination of EEG + VR can assist in providing valuable insights into the effects of designed and built environments on users when employed as a complementary method alongside other established methods. However, it is important to acknowledge the inherent complexity of the brain and the limitations of assigning specific brain waves to precise activities. The brain operates through a sophisticated and intricate mechanism, and the relationship between brain waves and cognitive, emotional, or behavioural responses is an area of ongoing research and discovery (Li, Chao, and Zhang 2019).

While brain imaging technologies provide valuable tools for studying these relationships, they do not provide definitive answers and need to be interpreted with caution in light of the complexities of the human brain (Robinson 2015, 153). Therefore, rather than viewing EEG data as prescriptive guidelines, we should approach them as suggestive insights that inform the design process without imposing rigid constraints. While EEG data may indeed reveal patterns of neural activity associated with positive affect or cognitive engagement in response to certain design features, it is critical to acknowledge that these findings do not serve as universal prescriptions for all architectural contexts. Architectural environments are experienced as cohesive wholes that evoke certain reflection in users, an experience that cannot be reduced and assigned solely to individual elements. Instead, every environmental element is context-oriented and requires examination within its own unique context.

3. Proposing a design model integrating EEG + VR

3.1. Classification of existing design process models

In response to the second question regarding which stages of the design process can potentially incorporate user input, this section scrutinises various design process models to assess the current state of user involvement and pinpoint potential stages for integrating human experience through EEG and VR. Various architectural design process models have been proposed and discussed by researchers, such as Marcus and Maver, Archer, March, Rittel and Webber, Pahl and Beitz, and French (Figure 4). According to Cross and Roozenburg, these efforts have contributed to the formulation of fundamental principles that have gained consensus among the majority of researchers (Cross and Roozenburg 1992, 331).

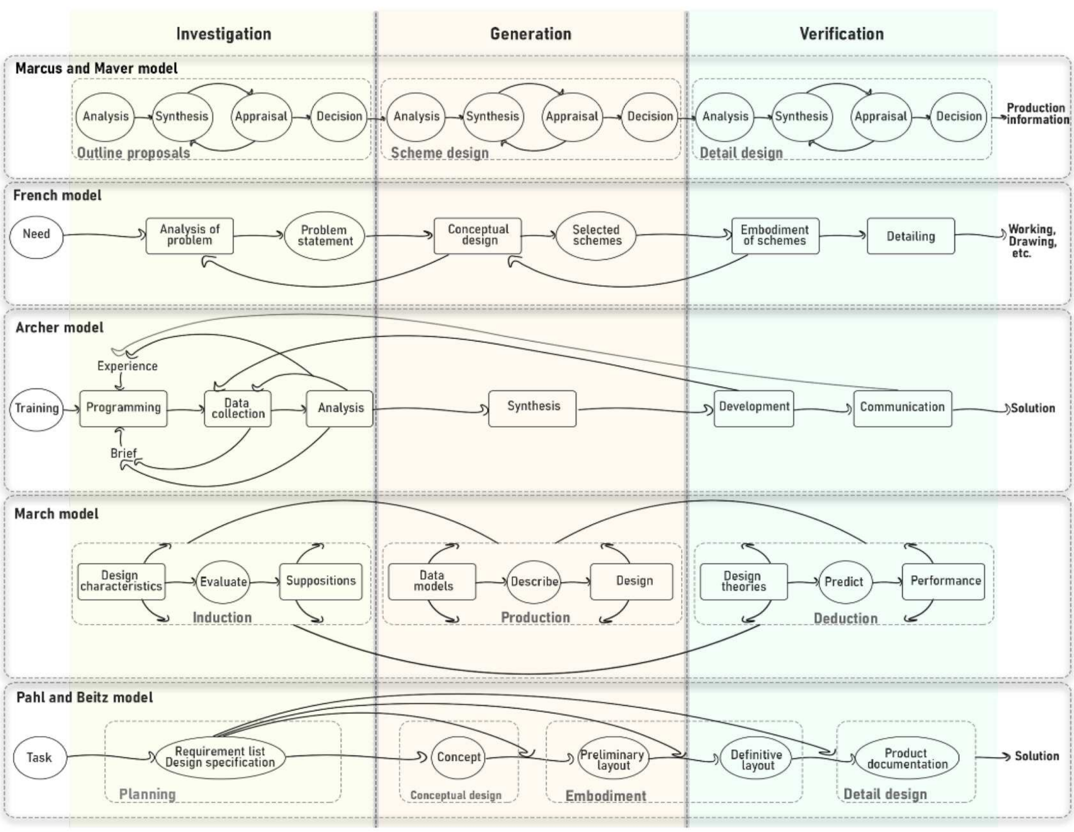

Figure 4. Classification of design process models (Illustration by the author). From top to bottom: Marcus and Maver model (Lawson, [1997] 2006, 43), French model (French 1971), Archer model (Cross and Roozenburg 1992, 329), March model (Cross and Roozenburg 1992, 331), Pahl and Beitz model (Beitz, Pahl, and Grote 1996).

To compare the integrated phases of the design process and assess the current state of user involvement, in Figure 4, the five renowned design process models are classified according to three shared phases: investigation, generation, and verification within the design process. During the investigation phase, the primary focus is on analysing the design problem and its prerequisites, examining the collected data, and formulating a plan for the way forward. In the subsequent generation phase, the designer synthesises the insights gained during the exploration phase and conceptualises potential solutions to create a schematic design. Moving into the verification phase, the preliminary layout is developed and assessed based on the findings from the preceding phases, with additional details incorporated into the plan to execute the solution. Throughout this iterative and reflective process across phases, a design solution is progressively developed.

Within the design process, designers continuously refine and enhance their understanding of the design problem and solution through an iterative process (Cross and Roozenburg 1992, 331). The RIBA Design Plan of Work, a widely recognised contemporary design model published by RIBA in 2020 and significantly revised over the years, delineates the stages where user contributions are anticipated. It includes Stage 0, which reviews feedback from previous projects; during concept design, which involves project reviews with stakeholders; and two stages of post-occupancy evaluation after construction, both upon completion and during the use of the space.[4] However, real-time user experiences are not included in these design models and are primarily based on passive information or feedback from previous similar projects and responses to questions. Traditional models tend to emphasise the designer's perspective, often overlooking the importance of user involvement. They do not systematically incorporate real-time user involvement or feedback as a key component in the design stages. Additionally, even in more recent models, the methods for collecting user feedback are limited to verbal questions and subjective responses, which risk self-censorship or manipulation and lack an evidence-based approach (Bargh and Chartrand 1999; Ramachandran and Hirstein 1999).

Based on the classification of the existing design models and the experiment findings, the next section proposes a design model that anchors users within the design process through a set of strategies incorporating EEG + VR methods and integrating user experience feedback into the design process.

4. A neuro-architectural design model integrating EEG + VR

The experiment findings of the first stage, presented in Section 2.4, confirmed the significant potential of EEG in discerning user experiences under various conditions, as well as the suitability of combining EEG and VR to provide valuable insights into the effects of designed and built environments on users. In the second phase, we identified the stages of the design process that could potentially incorporate user input by classifying the existing design models, as illustrated in Section 3. Building on the insights gained from both stages, this paper proposes a foundational design process model, depicted in Figure 5, to effectively integrate users into the design process using EEG and VR. As a foundational model, it is open to further development.

Stages that have the potential to incorporate users' feedback and experiences into the process are depicted in Figure 5, which involves users in three phases. Firstly, during the analysis of the task, along with requirements dictated by policies and standards for a specific building function, user demands obtained from interviews could be addressed. Additionally, according to the RIBA Design Plan of Work, insights from user feedback gathered in previous similar projects could provide valuable perspectives.

The classification of existing design models showed that the generation phase is a crucial stage where conceptual design evolves into preliminary design through a reflective and iterative process, incorporating user feedback to achieve desirable outcomes for both the user and the designer. Based on the findings of the experiment and the suitability of EEG in revealing differences in human experience under various conditions, the user's experience could be integrated by employing cognitive neuroscience techniques along with behavioural methods throughout the generation phase. Additionally, as the experiment confirmed the comparability of VR and physical conditions, using the representation of the designed environment in VR could provide an immersive space to investigate users' experiences with EEG.

In the third stage, the final layout is double-checked against the initial project targets to assess whether it adheres to project's requirements. After construction, the existing method of post-occupancy survey could assist in collecting users' reflections and responses to the built space, while the new method of EEG could be employed to gain insights for future projects. Therefore, concerning the usage of EEG + VR in the design model, EEG could be utilised in both the generation and verification stages, while VR could be employed specifically in the generation phase of the design process.

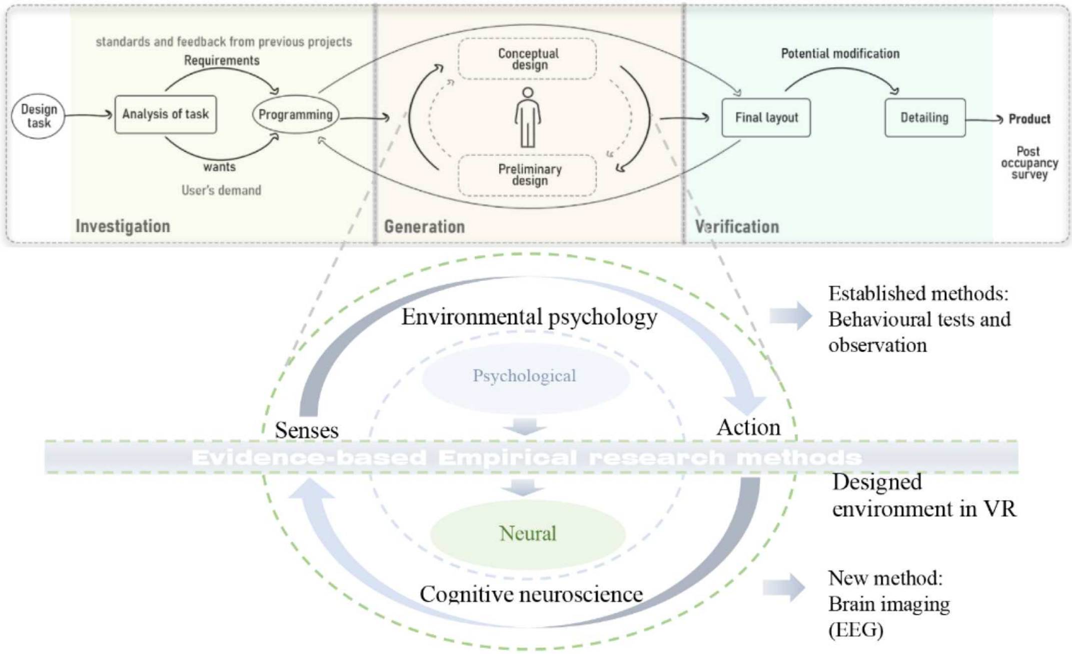

Figure 5. User-centred design process model integrating user experience through the application of behavioural methods and cognitive neuroscience in representation of the designed environment in VR.

Introducing the strategies of the proposed design model, the following section elaborates on its objectives, scope, methods involved, a protocol for implementing these methods into the process, application of this model across various building types, and the data analysis of the methods utilised in this design process model.

1. ***Objectives:*** This proposed model aims to facilitate a collaborative platform that enables users to share their comments comprehensively, capturing and integrating user experiences to evolve from conceptual design to preliminary design through an iterative and reflective process. Employing EEG can assist designers in becoming aware of user feedback while experiencing the environment, which may not be possible to capture through consciously given responses or verbal conversations. Additionally, considering the comparability of VR and physical conditions, VR can assist designers in enhancing their sense of empathy towards future users throughout the design process (Ryokai et al. 2022, 15; Toumi, Girandola, and Bonnardel 2021, 202), facilitating the internalisation of the user experience through an imaginative process (Pallasmaa 2015, 55).
2. ***Scope:*** To conduct this process, a designer needs to be trained in various disciplines or assemble a team of individuals with expertise in several areas. In addition to architectural knowledge, a basic understanding of human–computer interaction, environmental psychology, cognitive neuroscience, and statistical analysis is necessary. Knowledge in these fields of research is required to address the following needs:

- Representing the designed environment in the latest game engine and providing user interfaces in VR to showcase design alternatives.
- Employing behavioural and psychological tests and interpreting their results.
- Installing EEG devices, recording brain signals, preprocessing collected data, extracting desired features, and analysing them based on the latest findings in neuroscience and neuroarchitecture.
- Analysing the numerically extracted features and other quantitative cognitive or psychological measurements using statistical tests.

3. ***Methods:*** The market offers a wide range of EEG devices with varying features. The review of empirical studies (Taherysayah et al. 2024) revealed the usage of diverse EEG tools, influenced by factors such as project budget, the research team's proficiency in device utilisation, and analysis time constraints. The table below presents the number of channels utilised in these studies (Table 1).

Table 1. The number of EEG channels used in the reviewed studies.

Number of EEG channels	128	64	57	32	24	14	<10
Number of studies	3	1	2	3	1	3	6

VR devices and game engines are rapidly evolving, offering a range of options for designers to choose from based on their desired features. The current VR game engines offer the opportunity to model various alternatives within a single project, enabling users to interactively modify the environment while experiencing it.

4. ***Protocol:*** The EEG + VR method requires a protocol to be incorporated into the proposed model. This protocol is intended to be employed in the second stage of the proposed design process, specifically during the generation phase, which is the transition from conceptual design to preliminary design. Rather than solely relying on users to articulate their desired needs, the model suggests presenting alternatives and inviting users to experience them while their brain waves are being collected. Recording individuals' brainwaves must maintain ethical standards and participant trust throughout the process, including participant consent, confidentiality, and data security. Integrating interactive cognitive tasks during data recording would be advantageous, as it engages the user actively rather than passively (Taherysayah et al. 2024). EEG data, cognitive tasks, psychological and behavioural tests, and feedback forms across various alternatives and conditions proposed by the designer are then collected. These alternatives could encompass various scales, ranging from environmental features such as colour, scale, or elements like the size or shape of openings, to different design styles.

The research team compares and evaluates all collected data, including the EEG data based on the latest findings in neuroscience, which associate brain waves in specific regions of the brain with cognitive or emotional states. This step provides designers with insights into how well the designed environment aligns with users' expectations and the cognitive or emotional properties of the project. It is important to note that designers, as experts in configuring the environment, should design the space based on what they deem appropriate. However, it is the user who must experience that configuration over an extended period of time (Friedman 1972, 48). Therefore, while acknowledging the essential role of designers in the design process, it is also their responsibility to balance between the user's expectations and the environmental benefits they recognise.

As depicted in Figure 6, if the user's cognitive or emotional expectations of the project are addressed with the designed alternative or a combination of alternatives with minor revisions, the process proceeds towards making preliminary design. However, if their reflection reveals significant differences between the feature of project alternatives and user demands, the process should be repeated based on collected feedback. This circular process continues until an acceptable result is achieved, incorporating cognitive, emotional, or functional feedback from the project. In the next stage, presenting the preliminary design, the user is invited to

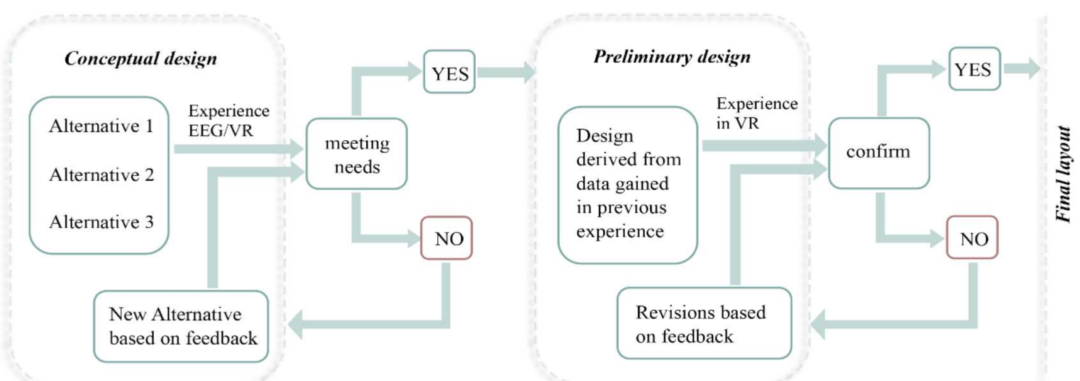

Figure 6. The process of evolving the design from conceptual to final layout.

experience the environment in VR, with or without EEG. While the application of EEG in this step is beneficial, due to the time-consuming data analysis, its use could be limited to the conceptual design stage. If the user is satisfied with the design, the process advances to finalise the design and detailing. If not, the cycle repeats until satisfactory feedback is obtained.

5. ***Building types:*** Different types of buildings require the investigation of different user groups through the design process, utilising EEG and psychological tests. (Figure 7)

A. *Private environments with specific users:* This category pertains to buildings or spaces designed for particular individuals or groups, such as residences, personal offices, or specialised facilities. Since these projects are private and personal to a specific user, it is recommended to conduct the experiment through a *within-subjects*[5] study, enabling users to experience all alternatives and collect their reflections.

B. *Public environments with long-term users:* This category includes public buildings or spaces that accommodate various user groups over an extended period, such as hospitals with specialised departments, universities with various academic departments, or office buildings with multiple tenants. In this category, it is recommended to employ cognitive or interactive tasks for users experiencing the environment, conducting a *between-subjects* study to involve different participants for different conditions or alternatives. Finally, the average outcome of each group of subjects collected from each alternative is compared to finalise the evaluation of the designed environment.

C. *Public environments with temporary users:* This category encompasses public buildings or spaces used by a transient population, such as airports, train stations, or event hubs. This category does not necessarily involve cognitive tasks and could be *within-subjects*, employing a group of participants with diverse demographic features to experience all alternatives and assisting designers in collecting more feedback on each alternative. Finally, the average outcome of each alternative is compared to finalise the evaluation of the designed environment.

6. ***Data Analysis:*** The most critical step of this model is data analysis and evaluation. The accuracy of EEG data depends on the precision of its collection. Screen and video recordings during the session assist in segmenting the collected data into desired intervals and eliminating unwanted moments. Preprocessing the data and artefact removal using methods like independent component analysis (ICA) (Lee 1998) and bandpass filtering prepare the data for feature extraction. There are several features that can be extracted from pre-processed data, such as Temporal Features, Frequency Domain Features, Time–Frequency Features, Spatial Features, and Connectivity Features.

Statistical tests and software like SPSS can assist the team in identifying significant or slight differences between frequency band powers obtained during different alternatives. Considering the nature of EEG data, which is often regarded as non-parametric (Maris and Oostenveld 2007), tests like the Kruskal–Wallis Test for *between-subjects* studies and the Wilcoxon Signed Ranks Test for *within-subjects* studies can be employed. Additionally, extracting boxplots of frequency band powers can provide a comparative platform to identify even slight differences between alternatives. Both significant differences between frequency band

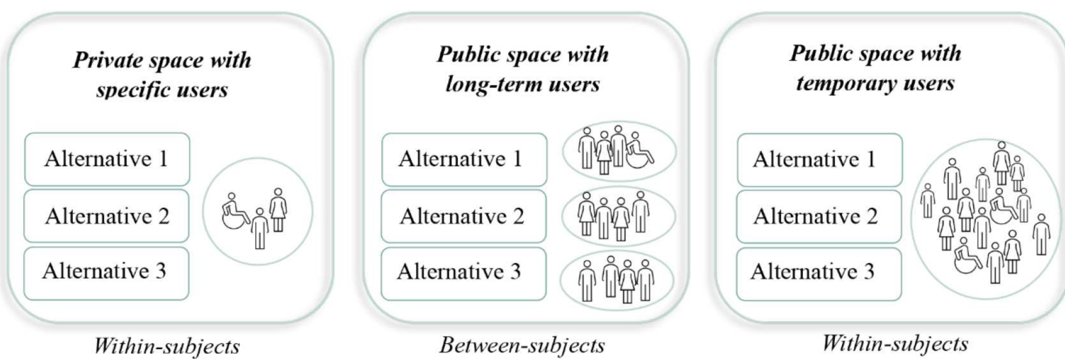

Figure 7. The integration of users into the design process of buildings with different functions.

powers and different band power distribution patterns across various alternatives, based on the latest findings of neuroscience and neuroarchitecture, provide insights into the environmental effect on users. If any psychological or cognitive tests are also performed during the session, they should be analysed and investigated for any differences using statistical analysis.

Conducting such exploratory and experiment-based design processes could help to create a collection of data about the effect of different environmental features on its users, which is currently lacking. Repeating this process in numerous projects can mitigate inconsistencies and confirm or refute existing findings, leading to a reliable common ground and understanding of the process of identifying the effect of the environment on users and recognising users' needs and desires in different functions of buildings. The infographic outlining the set of strategies for integrating users into the proposed model is presented in Figure 8.

5. Conclusion

Given the integral nature of the body–brain system and the interconnectedness of the body, brain, and environment (Mallgrave 2015a, 23), it is crucial to investigate human experiences within the environment and to reintegrate the user into the design process. In the initial stage, this study conducted a series of experimental phases to explore the suitability of employing EEG in collecting users' responses and reflections on the environment, as well as to compare the VR experience with physical conditions. In the second stage, pinpointing stages of the design process to potentially incorporate user input, classified the existing design models and consequently developed a design model.

Coming together, this study confirmed the suitability of employing the EEG + VR method and proposed its application through the developed design model. This paper, introducing the strategies of the proposed design model, elaborated on its objectives, scope, methods involved, protocol for implementing these methods into the design process, application of this model across various building types, and the data analysis of the methods utilised in this design process model. This model could enable architectural researchers to explore the relationship between the environments they are designing and human experiences. The insights gained from such investigations can be fed back into the design process.

Given the rapid advancements in both VR and brain imaging technologies, it is foreseeable that the utilisation of these tools will become less challenging and more convenient in the near future. Although the utilisation of neuroscience methods in architectural research holds substantial potential for evaluating the effect of designed spaces on users and assessing their spatial quality, it is critical to acknowledge that these findings should not serve as universal prescriptions for all architectural contexts. Architectural environments are experienced as cohesive wholes that evoke certain reflections in users, an experience that cannot be reduced and assigned solely to individual elements. Instead, every environmental element is context-oriented and requires examination within its own unique context.

5.1. Limitations and future work

To compare EEG data in physical and virtual settings, the experiment was conducted in both a real office space and a VR office space while participants performed a creative task. While this project compared the physical office space with its VR replica, the environment with high aesthetic quality, i.e. *Room Blue*, was implemented only in VR due to budgetary and time constraints of this research project.

Environments impact users over time, and it is possible that effects observed in a short-term study are transient and fade over time (Banaei et al. 2017), or that prolonged exposure to certain environmental features attenuates their effects (Song et al. 2022). Therefore, long-term studies will need to be conducted to provide insights into the variation of environmental effects on users. In addition, integrating insights from long-term studies into the proposed design process model will be important.

Neuroscience methods in architecture, while showing significant promise, are in development. Models are ways to integrate new approaches more systematically and require refinements over time. Our proposed model is a step towards a methodological approach to include neuroscience techniques like EEG measurements and new technologies such as VR in the design process in architecture. Further exploration is needed to identify the challenges associated with the proposed design process model and its strategies, outlined in Section 4, and to develop it accordingly. Furthermore, the potential of machine learning methods, algorithms, and classifiers in developing predictive models within the proposed design model can be investigated.

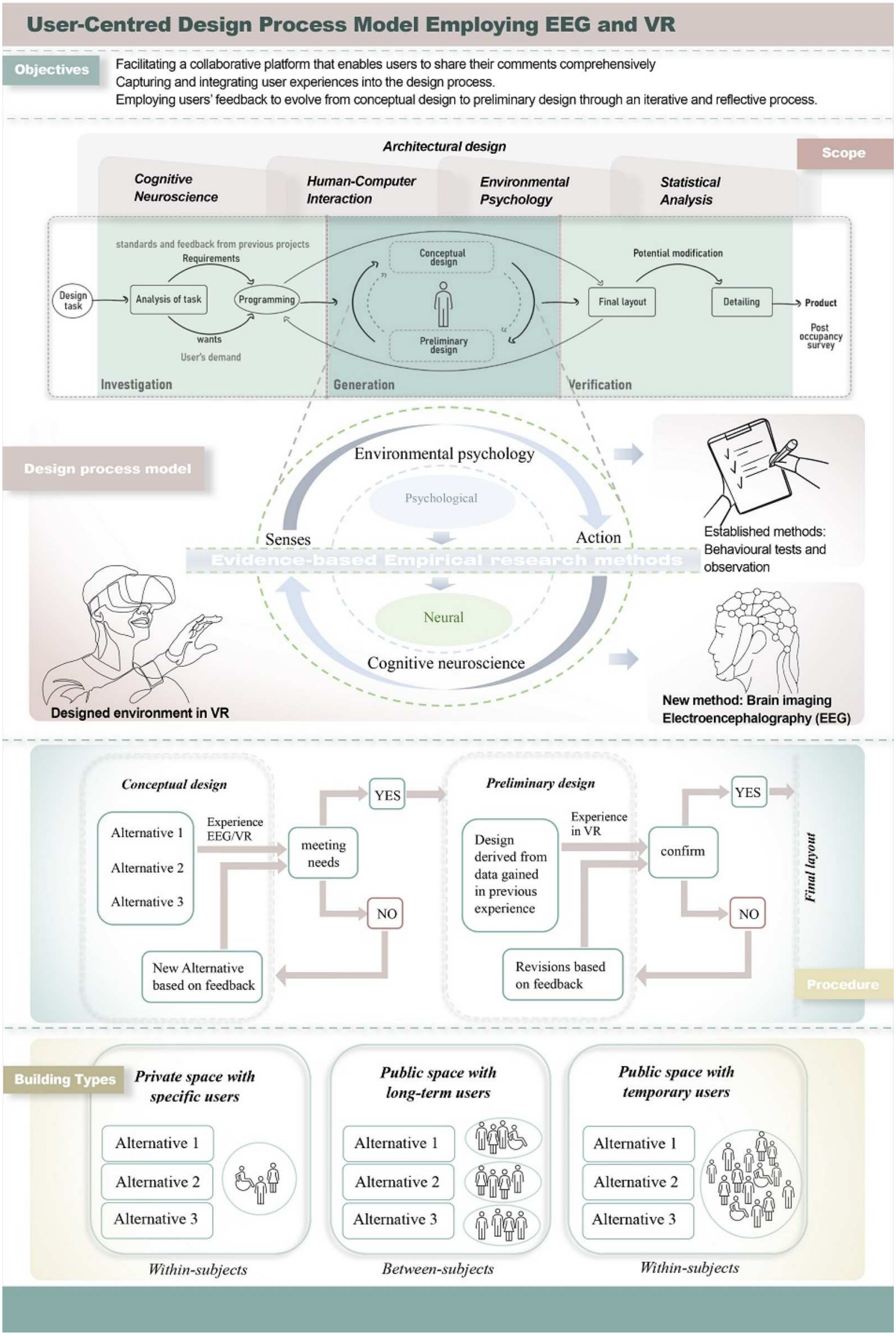

Figure 8. Infographic illustrating the proposed design process model, highlighting its objectives, scope, methods, protocol, and application across various building types.

Notes

1. *Neuroplasticity* underscores the brain's capacity to transform and compensate for neuronal loss through changes in experience and interaction with the environment (Gage 2003; Allam 2019, 122; Gatto 2020).
2. The *mirror mechanism* implies that the actions of other individuals or objects are mapped onto our own body representations through mirroring activity, often occurring unconsciously (Hustvedt 2010, 24).
3. Supplementary data to this research are deposited online at https://github.com/Mehraz90/Research-data
4. For more information, please refer to: https://www.architecture.com/knowledge-and-resources/resources-landing-page/riba-plan-of-work
5. *Within-subjects* study involves analysing responses from the same individuals across different conditions, while *between-subjects* study compares responses between different groups of participants.

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Noes on contributors

Dr Fatemeh Taherysayah is a PhD graduate from both Xi'an Jiaotong-Liverpool University and the University of Liverpool. Her research, positioned at the intersection of architecture and neuroscience, focuses on reintegrating users into the design process and investigating the effects of environments on cognitive activities.

Dr Claudia Westermann is a Senior Associate Professor in Architecture at Xi'an Jiaotong Liverpool University and Vice President of the American Society for Cybernetics. Her key areas of interest include art/science approaches to critical systemic practice, digital tools for place-making, and applications of neuroscience methods in spatial and interaction design.

Dr Hai-Ning Liang is an Associate Professor in the Computational Media and Arts Thrust at the Hong Kong University of Science and Technology (Guangzhou). His research focuses on human-computer interaction, with an emphasis on designing novel interaction techniques and applications for virtual, augmented, and mixed reality, as well as gaming and visualisation technologies.

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