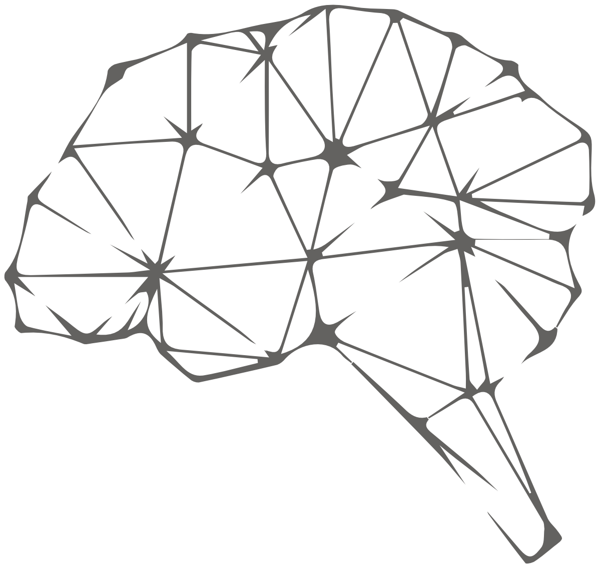


SOFIE GUSTAFSSON

# NEUROARCHITECTURE

The Measurability of Humans Emotional and Physical Response to Built Environment

# NEUROARCHITECTURE

The Measurability of Humans Emotional and Physical
Response to Built Environment

MASTER THESIS

Master Thesis in Architecture
Sofie Gustafsson
NTNU - Spring 2021

Master Thesis in Architecture
The Norwegian University of Science and Technology
Faculty of Architecture and Design

Supervisor: Bjørn Otto Braaten
Student: Sofie Gustafsson

# Contents

# Acknowledgements

I would like to add a few words of appreciation for the people who has been a part of this process.

First of all, to my family and friends. Especially my parents, who have always supported me with love, encouragement and patience. Without you, I could never have reached my goals. Secondly, my supervisor, Bjørn Otto Braathen and staff at NTNU whom has offered valuable advice and guidance throughout this project. Lastly, I would like to express my gratitude to the special people whom I have befriended during my eight-year-long academic journey.

Thank you all for your support.

*We shape our buildings*
*and afterwards our buildings shape us.*

WINSTON CHURCHILL

# Preface

I was initially introduced to neuroarchitecture last year. I had just moved into my new apartment and was listening to a podcast whiles unpacking. In the podcast, a 'neurodesigner' was talking about her new book called 'Designfulness'. She explained how recent discoveries in neuroscience have led to a better understanding of how architecture and design affect our well-being. The wet autumn weather and ongoing pandemic kept me indoors most of the time, and I started to reflect on how the interior environment affected my mental health. I was intrigued by what I just had learned and ordered the book the same night.

This was the beginning of an insightful, but at times also overwhelming journey. When I started my thesis work, I knew close to nothing about neuroarchitecture and had no previous experience in writing systematic reviews. Looking back, I could not have imagined the amount of work this project required. I have spent countless hours learning about neuroscience, study designs, statistics, academic writing, and I have read hundreds of research papers. It has been a very rewarding and interesting experience, but also challenging at times. There is currently no staff or researchers at the Faculty of Architecture and Design at NTNU that have experience in neuroarchitecture, which limited the availability of support and supervision.

Initially, I planned to perform experiments and conduct a study. The experiment was planned to use EEG to collect data from test persons visiting IKEA and the Nidaros Cathedral, and then study how the participants experienced the two contrasting spaces. After consulting a professor in neuroscience at the faculty of medicine and health sciences, NTNU, I sadly had to accept that it would not be possible to perform the experiment due to the current pandemic and the restrictions that made the involvement of test persons impossible.

Until recently, there have been very few studies on intuitive design and human responses to environmental stimuli. However, discoveries in neuroscience have provided data that gives us a physiological understanding of how the brain helps us navigate and react in built environments. Architects and neuroscientists are now working together using neurofeedback equipment to gather and then analyse data. The new field of evidence-based neuroarchitecture relies on neuroscience when making design decisions. This thesis provides an insight into the field of neuroarchitecture and how architects can benefit from recent scientific discoveries.

*Design is a frame for life.*

ILSE CRAWFORD

# Reading guide

The first six chapters are mainly theoretical and are included as an introduction to neuroarchitecture. Some information from the first chapters will be repeated in the systematic review for clarifying and informative purposes.

The systematic review is the main body of work. It is highly advised to read the appendices referred to in the review to fully understand the work.

The concluding chapter is a personal reflection on my findings and how I believe that neuroarchitecture can benefit the built environment in the future.

# Aims & Intentions

Neuroscience and Architecture are both comprehensive and complex fields involving a number of professions. The aim of this master thesis is to get a greater understanding of these two fields and how they come together to forms neuroarchitecture.

The subject I want to explore in my work is the cognitive and behavioural impact of spatial and architectural design. This thesis aims to study historical theories concerning the built environment and the human brain, subjective and objective measuring methods that are used to measure human responses to environmental stimuli and to evaluate to what degree neuroscience can contribute to improving architectural design.

Neuroarchitecture has become a trend that is portrayed by certain professionals and by the media as the 'solution' in creating ideal architecture. The history of architectural design does however tell us that such 'trends' can have a devastating outcome. By identifying aspects within Neuroarchitecture that can contribute and limit architectural design I will try to assess what role Neuroarchitecture will have in the future of architectural design.

# Thesis Questions

*What theories and methodologies exist and are appropriate to measure human responses to environmental stimuli?*

*What are the best suited quantitative research method to gather data for future studies in neuroarchitecture?*

*What findings are emerging from evidence-based studies, and to what degree can neuroscience contribute to improve architectural design in the future?*

# Methodology

I will first study and describe the brains anatomy and physiology, objective feedback techniques and subjective assessment methods. I will also explore how neuroarchitecture has developed since it was first described. The information will be gathered through literature research and online courses/ lectures.

I will then perform a systematic literature review to identify studies that are relevant to the topic, as well as to determine the prospects of further research. An iterative systematic approach will be used to assess the importance of specific criteria. This will help to define words that will be used in the literature search and distinguish relevant material.

Lastly, I will review and discuss my findings and what they tell about the limitations, contributions and future of neuroarchitecture.

**NeuroScience**

*A multilevel, multidisiplinary subject comprising morphological, functional and physical studies of the central nervous system*

(Shulman 2013, p. 59)

**NeuroAesthetics**

*A relatively young field within cognitive neuroscience, concerned with the neural underpinnings of aesthetic experience of beauty, particularly in visual art*

(Chinzia 2009, p. 682)

**NeuroArchitecture**

*Neuro-architecture unites architecture and neuroscience to better understand the relationship between the human brain and the surrounding built environment*

(Azzazy, 2020, p. 3)

# 1. Introduction

Architecture has the ability to merge perception, imagination and experience with the tangible spatiality. Since the dawn of human dwelling, intuition has been a key in creating environments where humanity can prosper. Theories about the relationship between 'the mind and the body' and 'the body and space', as well as the connects between architecture and anatomy, physiology, psychology, phenomenology and intuition have historically been of great human interest.

People spend most of their time surrounded by the built environment, from birth throughout life and ultimately death. Research shows that Europeans spend almost 22 hours a day indoors (World Health Organization regional office for Europe, 2013). Cities are continuously growing, and two-thirds of the world's population will live in urban areas by 2050. Consequently, the urban area will expand significantly to provide shelter and facilities for the 2.4 billion new inhabitants (Goldhagen and Gallo, 2017, United Nations Department of Economic and Social Affairs, 2018). Therefore, it has never been more critical than now to create sustainable built environments that promote good health and well-being.

In a world where we spend most of our time indoors, and climate changes and social issues have become a frightening reality, we can no longer afford to waste resources on unsustainable architecture. Humans need to constantly adapt to the built environment and all multisensory stimuli it entails. Neuroarchitecture can potentially give scientific insight into human response patterns in built environments. Such findings can inform architects during the design process and consequently positively impact the future of the built environment. Better knowledge about humans' cognitive and emotional responses to the built environments could be used to improve inhabitants' physical and mental health. Additionally, it may result in more efficient use of space with a beneficial impact on the building's functionality, quality, sustainability, and the economy.

## References

GOLDHAGEN, S. W. & GALLO, A. 2017. The Sorry Places We Live. Welcome to your world: How the built environment shapes our lives. Harper New York.

UNITED NATIONS DEPARTMENT OF ECONOMIC AND SOCIAL AFFAIRS 2018. World Urbanization Prospects: The 2018 Revision New York: United Nations.

WORLD HEALTH ORGANIZATION REGIONAL OFFICE FOR EUROPE 2013. Combined or multiple exposure to health stressors in indoor built environments. In: SARIGIANNIS , D. A. (ed.) An evidence-based review prepared for the WHO training workshop “Multiple environmental exposures and risks“. World Health Organization.

*The ultimate challenge—is to understand the biological basis of consciousness and the brain processes by which we feel, act, learn, and remember.*

ERIC R. KANDEL

# 2. Neuroscience

The mind has always fascinated humans. Quests to understand the brain dates back to early Greek and Egyptian civilisations. Ancient Greek history indicates that the nervous system was discovered already in the 3rd Century BC. Alcmaeon of Croton's medical writings, Praxagoras of Kos, theories involving neurons, and Herophilus of Chalcedon distinguishment between sensory and motor nerves are essential to our understanding of the brain and the nervous system (Panegyres and Panegyres, 2016).

A significant number of discoveries have since been made in the rapidly evolving field that we now know as neuroscience. A brief introduction to some historical findings that are relevant for both neuroarchitecture and the Norwegian University of Science and Technology (NTNU) are mentioned below:

Charles Darwin's was an English naturalist, geologist and biologist who made significant contributions in several scientific fields. Darwin's scientific theory of evolution by natural selection is considered the foundation of modern evolutionary synthesis. In 1873 Darwin suggested that animals navigate by using information about their own movement (self-motion cues) to determine their location in relation to the starting position (Whishaw et al., 2001).

Paul Broca was a French surgeon, anatomist and anthropologist. He is known best known for his contribution to the foundation of modern neuropsychology and cognitive neuroscience. In the 1860s, Broca studied patients with brain damage and found that different brain regions are responsible for specific functions. Broca's area is a region in the frontal lobe and is named after Broca due to his discoveries involving language expression (Cowan et al., 2000, Dronkers et al., 2007).

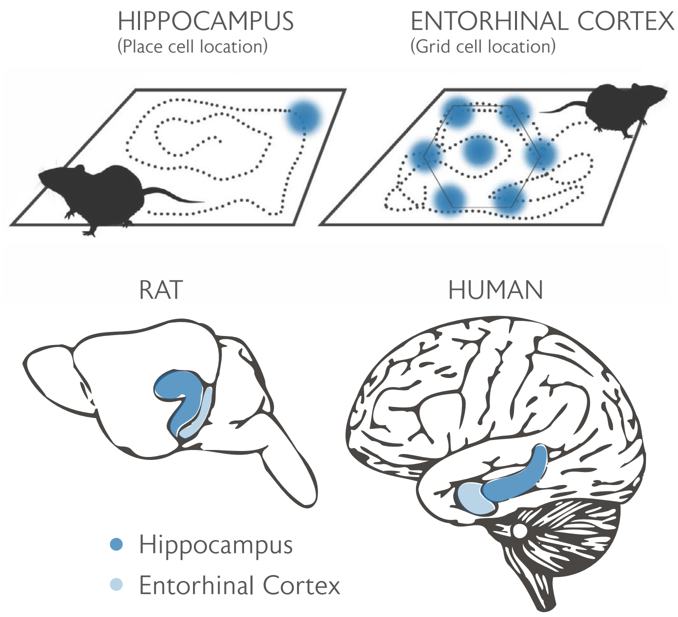



Figure 1 - The firing pattern of place cell and grid cells.
Adapted from Bjerknes and Moser, 2019

John O’Keefe and John Dostrovsky studied hippocampal function and memory in the 70s and were able to record the activity of hippocampal neurons (place cells) in rats. Each individual place cell fired when a rat was in a specific location, and combined, they created a representation of the entire space that the rat was occupying (O’Keefe and Dostrovsky, 1971). Further research also showed that the hippocampus is a structure that serves as an internal representation of the surrounding environment (cognitive map, O’keefe and Nadel, 1978).

Around 130 years after Darwin first voiced his theory, May-Britt Moser and Edvard Moser discovered the brain region that is specialised in navigation. The two scientists at NTNU described the grid cells (also present in humans) in the hippocampus’ input region of the brain, the entorhinal cortex. Recordings of a moving rodent within an enclosed space showed that a grid cell responds when the rodent is in a particular location. Those locations are spaced out and creating a hexagonal firing pattern that forms virtual maps of the surrounding environment (Moser et al., 2015).
Grid cells can also explain how memories are formed and how humans can envision spaces that they have previously visited (Abbott, 2014).

In 2014 John O’Keefe, May-Britt Moser and Edvard Moser were awarded the Nobel prize in Physiology or Medicine for discovering the function of these cells dealing with location and space, the “GPS system” of the brain.

Neuroscience is multidisciplinary and includes various fields, such as biology, genetics, medicine, psychology, chemistry, computer science, engineering, and mathematics. During recent years many discoveries and advances have been made due to the rapid progress and increase of technology (Kaiser, 2014). New scientific findings have provided a greater understanding of human psychological and behavioural needs and the functions of the pathological nervous system. The Society for Neuroscience predicts that this rapid growth will continue during the next 50 years, and new advances can improve human health, the economy, and society (Altimus et al., 2020).

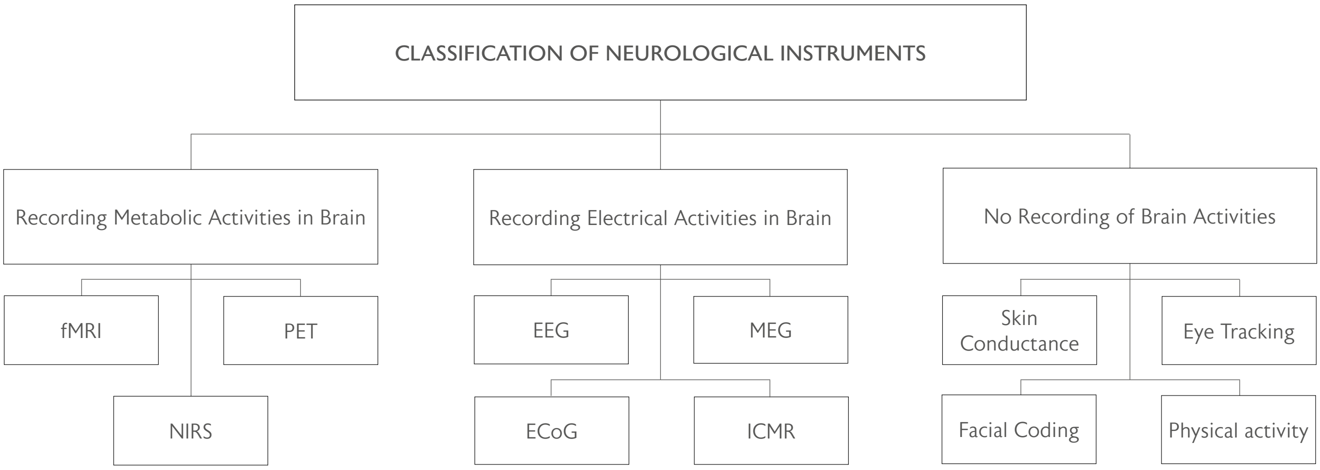



Figure 2 - Classification of Neurological Instruments.

| Implicit Technique | Measure's: | Temporal resolution | Spatial resolution | Neural signal | Invasive | Method type | Training | Cost | Portability |
|---|---|---|---|---|---|---|---|---|---|
| EEG | Electrical | High (1-4ms) | Low (~10mm) | Direct | No | Non-invasive | Some | Low | Stationary/ portable |
| ECoG | Electrical | High (~3 ms) | High (~1mm) | Direct | Yes | Invasive | Extensive | High | Stationary/ portable |
| ICNR | Electrical | High (~3 ms) | High (~0.5mm)* | Direct | Yes | Invasive | Extensive | High | Stationary/ portable |
| PET | Metabolic | Low (≥10s) | High (~5 mm) | Indirect | Yes | Non-invasive | Extensive | High | Stationary |
| fMRI | Metabolic | Low (1s) | High (~1mm) | Indirect | No | Non-invasive | Extensive | High | Stationary |
| NIRS | Metabolic | Low (1s) | High (~5mm) | Indirect | No | Non-invasive | Some | Low | Stationary/ portable |
| MEG | Magnetic | High (~5ms) | High (~5mm) | Direct | No | Non-invasive | Extensive | High | Stationary |

Table 1 - Common functional brain imaging techniques.
(iMotions, 2019, Koike et al., 2013, McLoughlin et al., 2014, Pandarinathan et al., 2018)

EEG = Electroencephalogram
EcoG = Electrocorticography
ICMR = Intra-cortical neuronal recording
PET = Positron emission tomography
fMRI = Functional magnetic resonance imaging
MEG = Magnetoencephalography
NIRS = Near-infrared spectroscopy

## 2.1. Functional Imaging Techniques

Functional imaging techniques, processor technologies, data analysis procedures, and algorithms have allowed researchers to better understand how the brain functions (iMotions, 2019). There are a variety of functional imaging techniques available, which are used for scientific, medical, educational and commercial purposes (see Table 1, p. 8). Substantial amounts of resources have been granted to the field of neuroscience in the quest to get a better understanding of human behaviour, experience and related diseases. Neuroscience is currently one of the most active areas of contemporary biology and medicine (Mancall and Brock, 2011). The new scientific advances have caught both scientists and the general public's attention. New discoveries will contribute to a better understanding the of organisation and function of the brain and consequently the treatment of mental and neurological disorders (Quaglio et al., 2017) The development of functional imaging techniques, processor technologies, data analysis procedures, and algorithms have allowed researchers to investigate the brain functions in greater detail (iMotions, 2019).

Some of the most common functional brain imaging technique are listed in Table 1, p.8.

Temporal resolution: *How closely the measured activity corresponds to the timing of the actual neural activity.*

Spatial resolution: *How the accurately the measured activity is localized within the brain (Cohen, 2009).*

| Band | Symbol | Lower (Hz) | Upper (Hz) | Amplitude Range (μV) |
|---|---|---|---|---|
| Delta | δ | 0.5 | 4 | 20-200 |
| Theta | θ | 5 | 7 | 20-100 |
| Alpha | α | 8 | 14 | 20-60 |
| Beta | β | 15 | 30 | 2-20 |
| Gamma | γ | 30 | 50* | 5-10 |

Table 2 - Normal Frequency Range of Ongoing EEG (in Hz, Cycles per second)
Based on information from Hughes, 2008

*40 Hz is typically used, although some have reported that gamma can range up to 100 Hz.

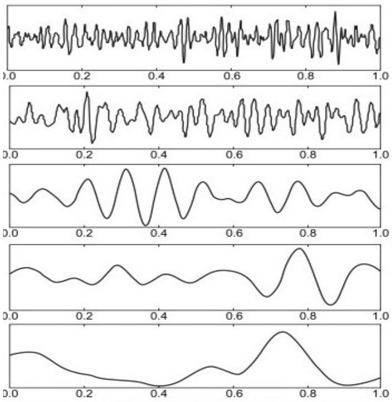



Figure 3 - Brain wave samples for different waveforms.
(Abhang et al., 2016)

## 2.2. Electroencephalogram (EEG)

In recent years there has been a rapid development of EEG equipment due to new and innovative digital technology. Today, EEG is a widely used method to analyse brain function in research and to diagnose medical conditions such as epilepsy and sleep disorders (Da Silva, 2009). EEG equipment has become a popular tool as it is relatively inexpensive, can be mobile, and is relatively easy to use.

EEG offers continuous recording of brain activity by measuring the differences in voltage (electrical potential) between two electrodes (see Table 2, p. 10). It is a non-intrusive method where electrodes are attached to the scalp. Modern EEG has a millisecond temporal resolution, and this means that it can produce thousands of images per second of the electrical activity from multiple electrodes. A disadvantage with EEG is its poor spatial resolution. The electrodes record the electrical activity from the scalp (surface) and cannot determine the exact source of the activity. However, advances in EEG acquisition systems and electric head modelling (3D models showing in which parts of the brain the activity takes place) have improved the spatial resolution of scalp EEG (Ferree et al., 2001). High-density EEG recording (64 - 256 channels) offers a higher number of solution points and therefore more spatial resolution, and somewhat better spatial accuracy. The accuracy, however, stops improving when the solution points exceed a certain number as the number of electrodes determines the quantity of input (Michel and Brunet, 2019).

The number of electrodes varies from 10 to several hundred, depending on the equipment and the size of the experiment. Several factors affect the price and accuracy of the EEG equipment. More expensive equipment usually has more electrodes, advanced digitalising software and an amplifier with higher sampling rates (Abreu et al., 2018, iMotions, 2019).

A range of technology and equipment is necessary to record reliable EEG data, including devices to deliver stimuli, an EEG headset to record brain activity, an EEG amplifier, and a computer to amplify, filter, and convert analogue electrical signals from the sensor into digital signals. The electrode that captures brainwave activity is called an EEG channel, and the number of channels determines the density (more detailed information) of the EEG recording.

Artefacts in EEG are signals recorded by EEG but not generated by the brain. EEG data can become affected by a variety of different artefacts that originate from internal and external sources. Internal sources of artefacts are caused by physiological activity and movement, while external sources of artefacts are due to environmental interferences, the recording equipment, electrode popping and cable movement. (Islam et al., 2016).

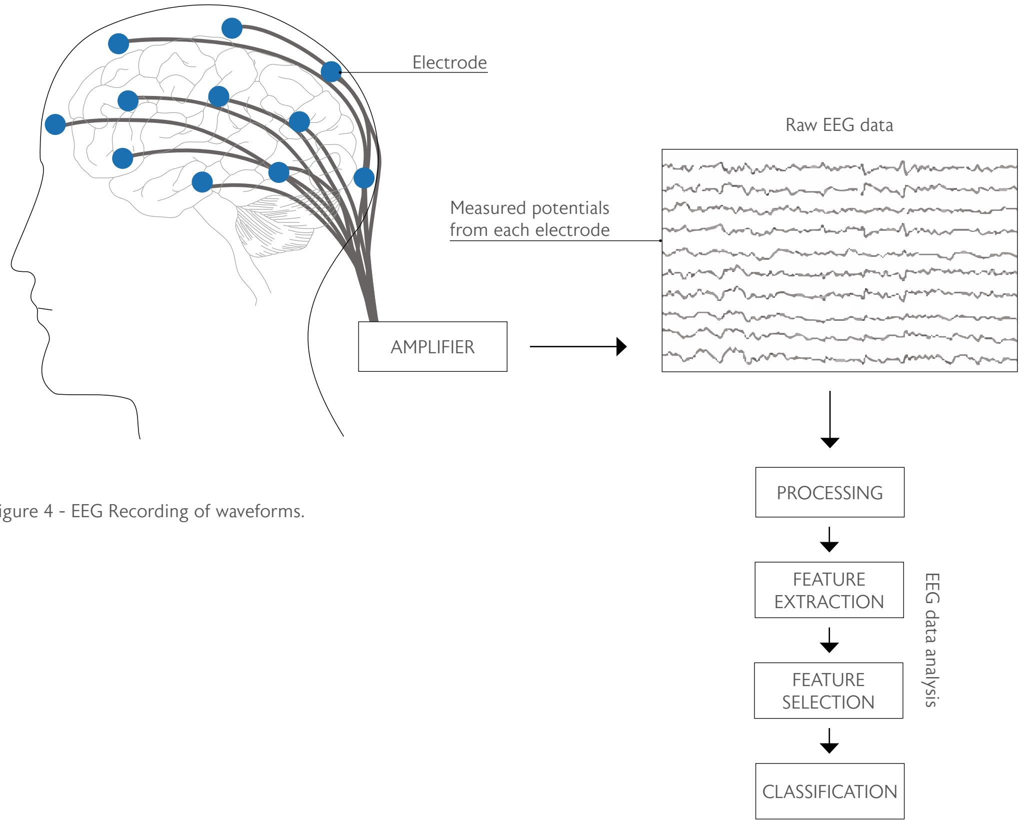



Figure 4 - EEG Recording of waveforms.

## Terminology

**Voltage:** Symbol V. An electromotive force or potential difference expressed in volts.

**Volt:** Symbol V. The SI unit of electric potential, potential difference, or electromotive force defined as the difference of potential between two points on a conductor carrying a constant current of one ampere when the power dissipated between the points is one watt. It is named after Alessandro Volta.

**Currents:** Symbol I. A flow of electric charge through a conductor. The current at a particular cross section is the rate of flow of charge. The charge may be carried by electrons, ions, or positive holes. The unit of current is the ampere.

**Resistance:** Symbol R. The ratio of the potential difference across an electrical component to the current passing through it. It is thus a measure of the component's opposition to the flow of electric charge. In general, the resistance of a metallic conductor increases with temperature, whereas the resistance of a semiconductor decreases with temperature.

**Frequency:** Symbol f or *v*. The rate of repetition of a regular event. The number of cycles of a wave, or some other oscillation or vibration, per second is expressed in hertz (Hz), cycles per second.

**Power:** Symbol P. The rate at which work is done or energy is transferred. In SI units it is measured in watts (joules per second).

**Phase:** A description of the stage that a periodic motion has reached, usually by comparison with another such motion of the same frequency. Two varying quantities are said to be in phase if their maximum and minimum values occur at the same instants; otherwise, there is said to be a phase difference.

(Rennie and Law, 2019)

## Tables & Figures

# References

ABBOTT, A. 2014. Neuroscience: Brains of norway. Nature News, 514, 154.

ABREU, R., LEAL, A. & FIGUEIREDO, P. 2018. EEG-Informed fMRI: A Review of Data Analysis Methods. Frontiers in Human Neuroscience.

ABHANG, P. A., GAWALI, B. W. & MEHROTRA, S. C. 2016. Chapter 2 - Technological Basics of EEG Recording and Operation of Apparatus. In: ABHANG, P. A., GAWALI, B. W. & MEHROTRA, S. C. (eds.) Introduction to EEG- and Speech-Based Emotion Recognition. Academic Press.

ALTIMUS, C. M., MARLIN, B. J., CHARALAMBAKIS, N. E., COLÓN-RODRÍGUEZ, A., GLOVER, E. J., IZBICKI, P., JOHNSON, A., LOURENCO, M. V., MAKINSON, R. A., MCQUAIL, J., OBESO, I., PADILLA-COREANO, N. & WELLS, M. F. 2020. The Next 50 Years of Neuroscience. The Journal of Neuroscience, 40, 101-106.

BJERKNES, T. L. & MOSER, M. 2019. A sense of place. Biologist, 66, p. 10-13.

COHEN, M. Electricity and Magnetism: Insights into the brain from multimodal imaging. 2009 Conference Record of the Forty-Third Asilomar Conference on Signals, Systems and Computers, 2009. IEEE, 1593-1597.

COWAN, W. M., HARTER, D. H. & KANDEL, E. R. 2000. The Emergence of Modern Neuroscience: Some Implications for Neurology and Psychiatry. Annual Review of Neuroscience, 23, 343-391.

DA SILVA, F. L. 2009. EEG: origin and measurement. EEg-fMRI. Springer.

DRONKERS, N. F., PLAISANT, O., IBA-ZIZEN, M. T. & CABANIS, E. A. 2007. Paul Broca's historic cases: high resolution MR imaging of the brains of Leborgne and Lelong. Brain, 130, 1432-1441.

FERREE, T. C., CLAY, M. T. & TUCKER, D. M. 2001. The spatial resolution of scalp EEG. Neurocomputing, 38-40, 1209-1216.

HUGHES, J. R. 2008. A review of recent reports on autism: 1000 studies published in 2007. Epilepsy & Behavior, 13, 425-437.

IMOTIONS 2019. Electroencephalography - The Complete Pocket Guide. iMotions.

ISLAM, M. K., RASTEGARNIA, A. & YANG, Z. 2016. Methods for artifact detection and removal from scalp EEG: A review. Neurophysiol Clin, 46, 287-305.

KAISER, U. B. 2014. Editorial: advances in neuroscience: the BRAIN initiative and implications for neuroendocrinology. Molecular endocrinology (Baltimore, Md.), 28, 1589-1591.

KOIKE, S., NISHIMURA, Y., TAKIZAWA, R., YAHATA, N. & KASAI, K. 2013. Near-Infrared Spectroscopy in Schizophrenia: A Possible Biomarker for Predicting Clinical Outcome and Treatment Response. Frontiers in Psychiatry, 4.

MANCALL, E. L. & BROCK, D. G. 2011. Overview of the Organization of the Nervous System. Gray's Clinical Neuroanatomy: The anatomic basis for clinical neuroscience Elsevier Health Sciences.

MCLOUGHLIN, G., MAKEIG, S. & TSUANG, M. T. 2014. In search of biomarkers in psychiatry: EEG-based measures of brain function. American Journal of Medical Genetics Part B: Neuropsychiatric Genetics, 165, 111-121.

MICHEL, C. M. & BRUNET, D. 2019. EEG source imaging: a practical review of the analysis steps. Frontiers in neurology, 10, 325.

MOSER, M.-B., ROWLAND, D. C. & MOSER, E. I. 2015. Place cells, grid cells, and memory. Cold Spring Harbor perspectives in biology, 7, a021808.

O'KEEFE, J. & DOSTROVSKY, J. 1971. The hippocampus as a spatial map. Preliminary evidence from unit activity in the freely-moving rat. Brain Research, 34, 171-175.

O'KEEFE, J. & NADEL, L. 1978. The hippocampus as a cognitive map, Oxford: Clarendon Press.

PANDARINATHAN, G., MISHRA, S., NEDUMARAN, A. M., PADMANABHAN, P. & GULYÁS, B. 2018. The potential of cognitive neuroimaging: a way forward to the mind-machine interface. Journal of Imaging, 4, 70.

PANEGYRES, K. P. & PANEGYRES, P. K. 2016. The Ancient Greek discovery of the nervous system: Alcmaeon, Praxagoras and Herophilus. Journal of Clinical Neuroscience, 29, 21-24.

QUAGLIO, G., CORBETTA, M., KARAPIPERIS, T., AMUNTS, K., KOROSHETZ, W., YAMAMORI, T. & DRAGHIA-AKLI, R. 2017. Understanding the brain through large, multidisciplinary research initiatives. Lancet Neurol, 16, 183-184.

WHISHAW, I. Q., HINES, D. J. & WALLACE, D. G. 2001. Dead reckoning (path integration) requires the hippocampal formation: evidence from spontaneous exploration and spatial learning tasks in light (allothetic) and dark (idiothetic) tests. Behavioural Brain Research, 127, 49-69.

Figure 1 - What is beauty?
(Da Vinci, 1503-1519)

# 3. Neuroaesthetics

Neuroaesthetics is studies on the biological mechanisms and psychological processes evoked by aesthetic experiences (Pearce et al., 2016).

Art reflects culture, society, religion, community, place and periods in time. These factors create aesthetic diversity and make art relatable to larger groups of people. Art itself might not be universal, but art as a whole is. Humans are not programmed to respond to art in a given way but are drawn to familiar and relatable objects (Nadal and Chatterjee, 2019).

German psychologist Gustav Theodor Fechner published the article 'Das Associationsprincip in der Aesthetik' (The Aesthetic Association Principle) in 1866 (Heidelberger, 2004, Ortlieb et al., 2020). Fechner argued that aesthetic choices are determined by the observer's previous experiences (associative factors) and by the object's formal properties (direct factors).

### Beauty

*The quality of being pleasing, especially to look at, or someone or something that gives great pleasure, especially when you look at it.* Cambridge dictionary.

Artists and philosophers have debated the relationship between beauty and goodness for centuries.

Recent neuroscientific evidence supports the idea that the function of aesthetic and moral judgement shares neural pathways. However, these studies are based on assumption and historical and philosophical discussions and not neuroscientific facts (Zaidel and Nadal, 2011). Another study found a connection between the brain's judgement of attractiveness and goodness. In the experiments, judgment of 'attractiveness' and 'goodness' was measured separately, which could have affected the outcome of the fMRI data (Tsukiura and Cabeza, 2011).

Anjan Chatterjee, neuroscientist and professor at the University of Pennsylvania, is one of the world-leading experts in the field. His research team has studied how the brain reacts to different environments, and the neural effects caused by aesthetic experiences. Chatterjee states that there are many questions that have not been answered yet and technical advances and more research is required (Chatterjee, 2014).

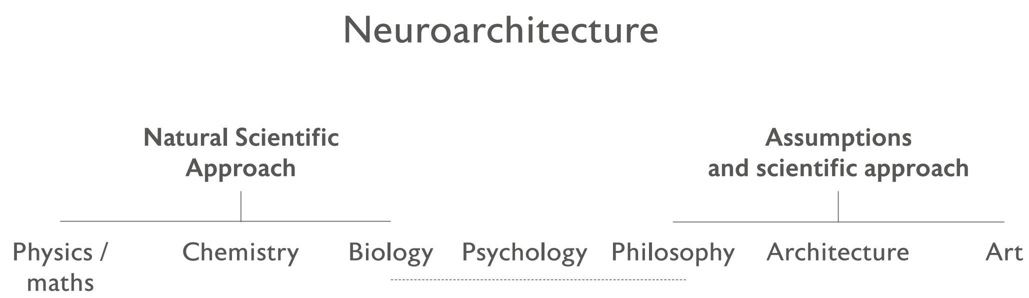



Figure 2: The relationship between neuroscience, neuroaesthetics and neuroarchitecture.

I argue that neuroaesthetics is a subfield of neuroarchitecture as it is only focusing on the visual and aesthetic experiences of an object, whilst neuroarchitecture comprehends the visual, spatial, auditory, olfactory, tactile and social aspects of a space (see Figure 2, p. 18).

## Figures

# References


CHATTERJEE, A. & VARTANIAN, O. 2014. Neuroaesthetics. Trends in Cognitive Sciences, 18, 370-375

DA VINCI, L. 1503-1519. Mona Lisa [Painting], The Mona Lisa Foundation, Available: http://monalisa.org/2012/08/16/the-earlier-version-through-the-magnifying-glass-2 [Accessed 20 April 2021

HEIDELBERGER, M. 2004. 'Life and Work'. Nature from Within: Gustav Theodor Fechner and His Psychophysical Worldview. Pittsburgh: University of Pittsburgh Press.

NADAL, M. & CHATTERJEE, A. 2019. Neuroaesthetics and art's diversity and universality. Wiley Interdisciplinary Reviews-Cognitive Science, 10.

ORTLIEB, S. A., KUGEL, W. A. & CARBON, C. C. 2020. Fechner (1866): The Aesthetic Association Principle-A Commented Translation. I-Perception, 11.

PEARCE, M. T., ZAIDEL, D. W., VARTANIAN, O., SKOV, M., LEDER, H., CHATTERJEE, A. & NADAL, M. 2016. Neuroaesthetics: The cognitive neuroscience of aesthetic experience. Perspectives on psychological science, 11, 265-279.

TSUKIURA, T. & CABEZA, R. 2011. Shared brain activity for aesthetic and moral judgments: implications for the Beauty-is-Good stereotype. Social Cognitive and Affective Neuroscience, 6, 138-148.

ZAIDEL, D. W. & NADAL, M. 2011. Brain intersections of aesthetics and morals: perspectives from biology, neuroscience, and evolution. Perspectives in Biology and Medicine, 54, 367-380.

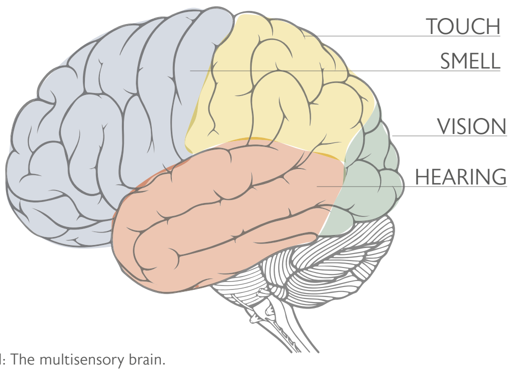


Figure 1: The multisensory brain.

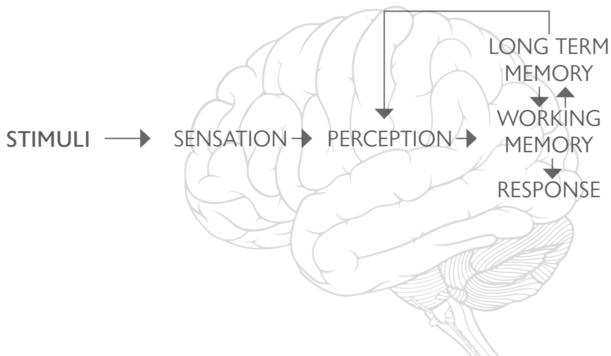


Figure 2: The brain's perception process.

# 4. Neuroarchitecture

Since the dawn of human dwelling, intuition has been a key in creating environments where humanity can prosper. Theories about the relationship between 'the mind and the body' and 'the body and space', and the connections between architecture and anatomy, physiology, psychology, phenomenology, and in-tuition, have historically been of great human interest. The term 'architectural determinism' was first used by the British planner Maurice Broady. In the article, 'The Social Context Of Urban Planning' (1969) Broday claims that the built environment can predict and determine social behaviour. Few professionals have since adopted this somewhat controversial idea, but many architects have voiced beliefs that architecture can affect human behaviour and wellbeing.

Subjective experiences and intuitive judgment have traditionally supported architectural theories and decisions. However, the development of research methods and technology has made it possible to incorporate scientific evidence in the architectural decision-making process. Architects and psychologist have, through empirical research, studied the correlation between human behaviour and the build environments since the 20th century (De Paiva and Jedon, 2019). Experience-based research uses assumptions to make conclusions regarding human behaviour, but not evidence-based data from experimental studies. The field of neuroarchitecture allows architects, psychologists, neuroscientists, and other disciplines to work together and investigate the short- and long-term cognitive and emotional impact of architectural spaces.

The brain has been described as "the most complex thing in the universe" (Pacitti et al., 2019) and it is intricate in both structure and function. Traditionally, the term 'neuroarchitecture' was used in neuroscience to describe the brain's form and function (Eberhard, 2009). The expression has been adopted by architects and neuroscientists and is now used to describe a multidisciplinary research field in which the relationship between the human brain and the built environment is studied (Azzazy et al., 2020). Neuroarchitecture thus connects the fields of neuroscience and architecture. Studies based on measurable neurological findings are relatively new, and the field of neuroarchitecture is rapidly evolving as new diagnostic methods develop. This opens up for new research and many intriguing hypotheses are yet to be tested.

There has recently emerged a growing interest regarding the mind's response to multisensory stimuli (Cross and Ticini, 2012, Spence, 2020). The temporoparietal junction (TPJ) is a cortical region of the brain that functions chiefly to evoke attention and social cognition, like managing high-level processes involving salient stimuli and reasoning about oneself and others (Bukowski and Lamm, 2017). Scientific findings show that the TPJ is a multisensory integration area (Ionta et al., 2011) that is essential in

*We must therefore avoid saying that our body is in space, or in time. It inhabits space and time.*

JUHANI PALLASMAA

self-location, also described as the ability to place and experience oneself in a physical space (Aglioti and Candidi, 2011). Multisensory integration is how the combined stimuli from different sensory systems affect processes in the nervous system (Stein et al., 2009). Multisensory stimuli should therefore be considered as necessary when doing experiments involving spatial environments.

Neuroarchitecture aims to better understand human neurophysiological and psychological responses to the built environment. EEG has become one of the most popular methods to record changes in brain activity both in neuroarchitecture and in other related fields. The technology is inexpensive and assessable, and the procedure is unintrusive. Electrical activity (Hz) is recorded via electrodes attached to the scalp. However, recording a person's emotional state has proven to be a complex task (Mauss and Robinson, 2009).

Like the Savanna Hypothesis, some theories argue that there are universal similarities regarding human aesthetic preferences (Joye, 2007). The brain's ability to read and understand a place has been essential for human survival and existence through history. Much of what we as humans take for granted today, such as modern surroundings, urban environments, and digitalisation, has only existed for a short moment in time. Sjövall explains that if human existence has lasted one day, humans have spent twenty-three hours and fifty-nine seconds on the African Savanna and only a fraction of the last minute in modern surroundings. Human spatial preferences are linked to the ancient parts of the brain and are still influenced by the will to survive on the Savanna either as a hunter or gatherer (Sjövall, 2020). However, the human brain is also plastic and can to some degree change its function to meet new challenges. The modern parts of the brain have evolved and significantly grown both in size and complexity since the time spent on the Savanna and has even been described as "the most complex thing in the universe" (Pacitti et al., 2019).

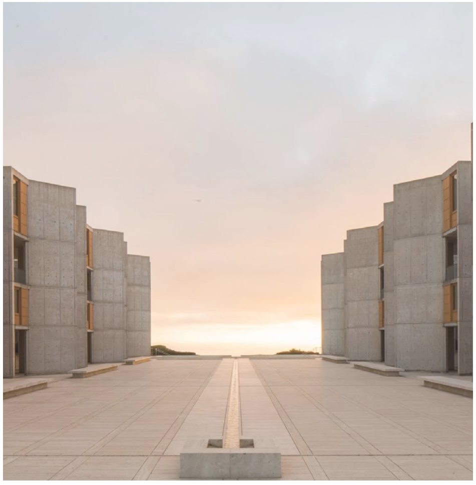


Figure 3 - The Salk Institute.
Daniels, 2017

### Salk Institute for Biological Studies

Jonas Salk encouraged collaboration between architects and researchers in the 1960s, long before the field of neuroarchitecture was established. Salk had spent many years in a laboratory, trying to find a cure for polio. Eventually, he decided to visit a $13^{th}$-century Franciscan monastery to clear his mind. During his stay at the monastery, Salk came to important insights that led to the discovery of the polio vaccine.
Salk later collaborated with architect Louis Kahn to design the Salk Institute, as he believed that the built environment can enhance creative ability (Sternberg and Wilson, 2006).

## Why is Neuroarchitecture important?

*What is it about a designed space that affects the human brain and how might understanding the response of the brain lead us to improvements in architecture in the future?*

*(Doughertya 2013, p. 5)*

New findings in the field of Neuroarchitecture can potentially give scientific exploitations to human response patterns in built environments. Such findings can inform architects during the design process and consequently have a positive impact on the future of the built environment.

More specific:
Users physical and mental health and a more efficient use of space will have a beneficial impact on the buildings functionality, quality, sustainability and materiality as well as on the economy and environment.

## NeuroArchitecture
## - the future of architecture?

*I believe that the future of this discipline is bright, and that neuroscientists and psychologists can foster good understanding of the needs of architects, designers and city planners to help them realise their visions in more successful ways.*

Dr. Oshin Vartanian

*There is, however, a risk that neuroarchitecture will become just another buzzword, a passing architectural fashion or a marketing exercise just as 'eco', 'green' and 'sustainable' have become.*

Ian Ritchie

# Figures

# References


AZZAZY, S., GHAFFARIANHOSEINI, A., GHAFFARIANHOSEINI, A., NAISMITH, N. & DOBORJEH, Z. 2020. A critical review on the impact of built environment on users' measured brain activity. Architectural Science Review, 1-17.

BROADY, M. 1969. The social context of urban planning. Urban affairs quarterly, 4, 355-378.

BUKOWSKI, H. & LAMM, C. 2017. Temporoparietal Junction. In: ZEIGLER-HILL, V. & SHACKELFORD, T. K. (eds.) Encyclopedia of Personality and Individual Differences. Cham: Springer International Publishing.

CROSS, E. S. & TICINI, L. F. 2012. Neuroaesthetics and beyond: new horizons in applying the science of the brain to the art of dance. Phenomenology and the cognitive sciences, 11, 5-16.

DANIELS, E. 2017. Restoration work completes on Louis Kahn's Salk Institute in California. https://www.dezeen.com/2017/07/06/salk-institute-restoration-biological-studies-louis-khan-restoration-wje-getty-conservation-institute/.

DE PAIVA, A. & JEDON, R. 2019. Short-and long-term effects of architecture on the brain: Toward theoretical formalization. Frontiers of Architectural Research, 8, 564-571.

DOUGHERTY, B. O. & ARBIB, M. A. 2013. The evolution of neuroscience for architecture: introducing the special issue. Intelligent Buildings International, 5, 4-9.

EBERHARD, J. P. 2009. Applying Neuroscience to Architecture. Neuron, 62, 753-756.

IONTA, S., HEYDRICH, L., LENGGENHAGER, B., MOUTHON, M., FORNARI, E., CHAPUIS, D., GASSERT, R. & BLANKE, O. 2011. Multisensory Mechanisms in Temporo-Parietal Cortex Support Self-Location and First-Person Perspective. Neuron, 70, 363-374.

JOYE, Y. 2007. Architectural lessons from environmental psychology: The case of biophilic architecture. Review of general psychology, 11, 305-328.

MAUSS, I. B. & ROBINSON, M. D. 2009. Measures of emotion: A review. Cognition & emotion, 23, 209-237.

PACITTI, D., PRIVOLIZZI, R. & BAX, B. E. 2019. Organs to Cells and Cells to Organoids: The Evolution of in vitro Central Nervous System Modelling. Frontiers in Cellular Neuroscience, 13.

RITCHIE, I. 2021. Neuroarchitecture: Designing with the Mind in Mind, John Wiley & Sons.

SJÖVALL, I. 2020. Back to Basics. In: ÅKESSON, B. (ed.) Designfullness. Stockholm, Sweden: Bokförlaget Langenskiöld.

SPENCE, C. 2020. Senses of place: architectural design for the multisensory mind. Cognitive Research: Principles and Implications, 5, 1-26.

STEIN, B. E., STANFORD, T. R. & ROWLAND, B. A. 2009. The neural basis of multisensory integration in the midbrain: Its organization and maturation. Hearing Research, 258, 4-15.

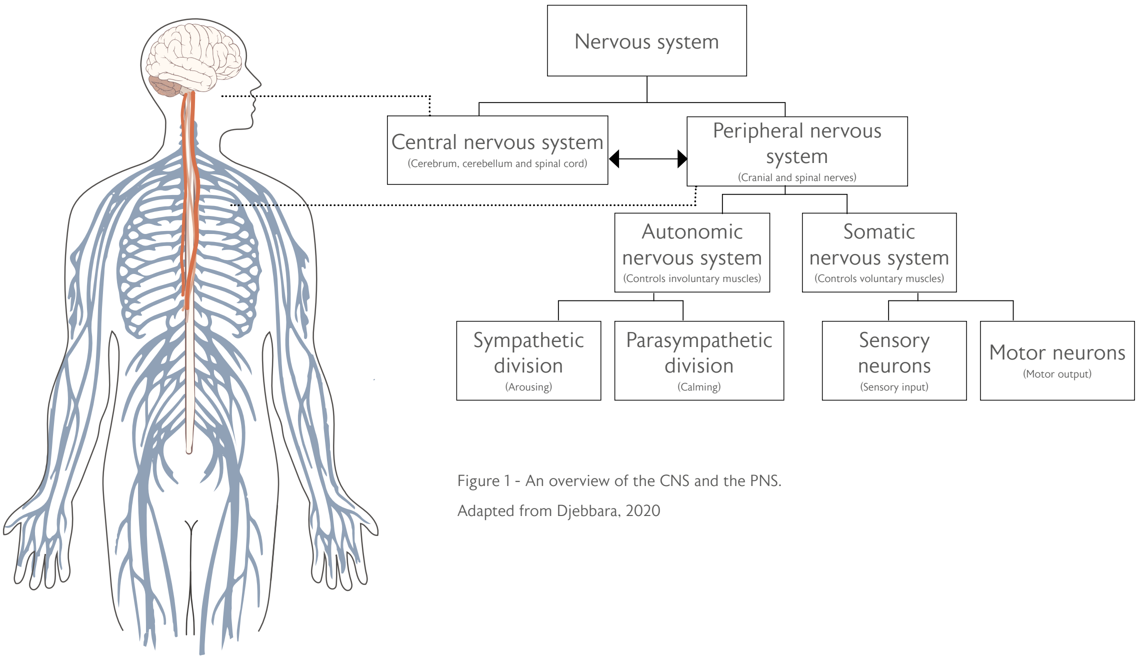



Figure 1 - An overview of the CNS and the PNS.

Adapted from Djebbara, 2020

# 5. The Nervous System

The complexity of the human nervous system is both evidence and a product of the biological evolution (Mancall and Brock, 2011). The brain is involved in most processes in the human body.
The brain's functions involved: select, sorts, and interprets information from the body and the environment, determine the body's internal and external behaviour (Brodal, 2010b).
The nervous system is subdivided into the central nervous system (CNS) and the peripheral nervous system (PNS):

- The CNS is made up of the brain (cerebrum and cerebellum) and the spinal cord.

- The PNS is made up of nerves that extend from the brain and spine, which makes it possible for the central nervous system to communicate with the body. (Brodal, 2010a). The PNS is further split into the somatic nervous system (SNS) and the autonomic (visceral) nervous system (ANS):
    - The ANS is associated with all structures excluding, the skeletal muscle (associated with the SNS). This includes regulation of involuntary movements such as cardiac function, respiration and other reflexes (Rea, 2015).
    - The SNS comprises all nerves that run to and from the spinal cord and are associated with skin and voluntary movements via skeletal muscles (Kapalka, 2010). Sensory (afferent) neurons receive stimuli from outside the CNS and convert them into internal electrical impulses, whiles motor (efferent) neurons transmits signals from the brain and spinal cord to muscle cells (Rea, 2015).

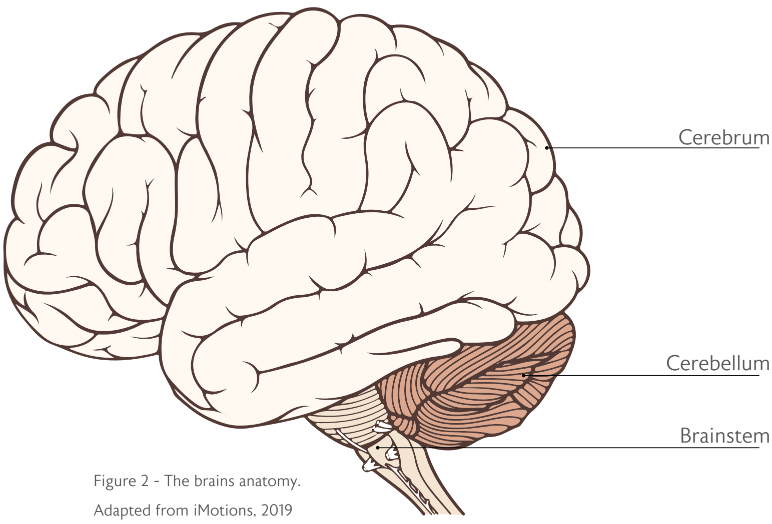


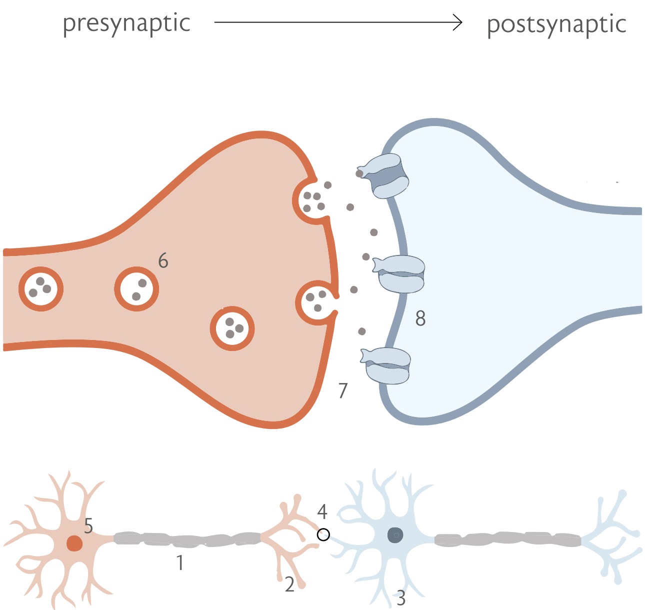

Figure 2 - The brains anatomy.
Adapted from iMotions, 2019

### The Cerebrum

The cerebrum (front of the brain) is the largest part of the human brain in volume. The ovoid-shaped brain area occupies most of the cranial cavity. It is folded and consists of two hemispheres that are nearly separated by a vertical slit. The corpus callosum is a bundle of nerve fibres that forms a bridge, carries information, and connects the cerebral hemispheres. The right hemisphere processes the signals from the left side of the body, and the left hemisphere processes signals from the right side of the body. The cerebrum enables consciousness as well as sensory and motor processing such as initiation- and coordination of movement, temperature, touch, vision, hearing, judgment, reasoning, problem-solving, emotions, and learning (Brodal, 2010a).

### The Cerebellum

The cerebellum (back of the brain), also known as 'the little brain', is located underneath the occipital lobe. It is the second-largest part of the brain and contains over half the brain's neurons (Carey, 2018). The cerebellum is highly folded, divided into two hemispheres, and necessary for carrying out various functions. It belongs to the motor system and involves functions such as the coordination and execution of voluntary movements, posture and balance (Brodal, 2010a).




1: Axon
2: Axon terminal
3: Dendrite
4: Synaptic terminals
5: Cell body
5: Synaptic vesicles
6: Cleft
7: Receptor

Figure 3 - The anatomy of a neuron.
Adapted from Jansen and Glover, 2020

## 5.1 Neurons

The nervous system is made up of two types of cells, called neurons and glia. The neurons sense and respond to internal changes in the body and external changes in the environment. (Crossman, Neary and Crossman, 2019). The cells encode and conduct information, sometimes over substantial distances and transmit signals to other neurons or non-neutral tissues such as muscles or glandular cells. The neuron has electrical properties and is the functional capabilities of the nervous system (Mancall, Brock and Gray, 2011).

Neurons are some of the longest-lived cells in the body. In a recent study, neurons continued to live past their life expectancy after being transplanted from a donor mouse to a longer-living rat. This research suggests that the organism's life length determines the neurons life. (Magrassi, Leto and Rossi, 2013)

Most neurons consist of a central mass of cytoplasm within a limiting cell membrane, termed the soma, or cell body which is the cells life support. Numerous branched processes known as neurites extend out from the soma. The dendrites pick up messages from other cells and send information towards the soma. The axon, usually much longer than other processes, transmits electrical impulses away from the cell body to other cells (Mancall, Brock and Gray, 2011).

Different types of neurons are classified by their number of dendrites and axons extending out from the cell body. The vast majority of neurons are multipolar neurons, with three or more processes. The multipolar neurons characteristically have one axon and several dendrites that extend from the soma. Most motor neurons or efferent neurons are multipolar. They transmit impulses from the central nervous system and out to the body's muscles and glands. Interneuron neurons (association neurons) are commonly multipolar neurons located in the central nervous system. They transmit impulses between sensory and motor neurons. Bipolar neurons have a centrally placed cell body with two processes, an axon and a single dendrite, extending from opposite sides. Bipolar neurons are located in sensory places like the afferent pathways of the visual, auditory, and vestibular systems. Unipolar neurons have one single process emerging from the soma, which divides into dendritic and axonal branches. Sensory neurons or afferent neurons are unipolar. Neurons of this type receive messages transmit impulses from sensory receptors, and send them towards the nervous system. (Watson, Kirkcaldie and Paxinos, 2010).

### Synapses

The synapse or the 'gap' is the communication links between cells. A nerve cell is separated, and the cell body has an electrochemical messaging system where neurons communicate by receiving and sending information across the nervous system. The transmission of information happens when signal molecules (neurotransmitters) are released and passes signals to other cells.

First, an action potential sends an electrical message to the synapse and then the signal is translated and sends it to another neuron. The process in which synaptic inputs are identified and nerve impulses are generated is called synaptic integration. The human brain has 100 million neurons, and each of these has 1000 to 10,000 synapses. Each of the hundreds of trillions of synapses can change and adapt its strength based on experience. This process gives the human brain the ability to learn and remember.

Nerves that send out signals are called presynaptic neurons, and the neuron that receives signals are called the postsynaptic neuron. Most neurons are, however, both presynaptic and postsynaptic. Two main types of synapses are called electrical- and chemical synapses. Electric coupling (gap junctions) are, however, most common in the glia. An electrical synapse sends an ion directly from the cytoplasm of one nerve cell to another over a gap junction to transmit neurological signals.

Chemical synapses turn electrical signals into chemical signals using neurotransmitters and then converts them back to electrical signals. This process gives the synapse the ability to modify, amplify, inhabit or split signals. Neurotransmitters help the brain to regulate necessary functions in the body by targeting specific cells (Crossman and Neary, 2014).

## Glia cells

Up until recently, scientists believed that the brain contains a higher number of glial cells than neurons. Recent findings, however, show that there is roughly a 1:1 ratio between neurons and glial cells (von Bartheld, Bahney and Herculano-Houzel, 2016). Glia has also proven to be far more important than previously expected. (Watson, Kirkcaldie and Paxinos, 2010) New research about the glia is rapidly emerging, but the complete understanding of glial cells functions is still unclear (Eroglu and Barres, 2010). A recent study concluded that glial cells are vital to all functions of the CNS and PNS. The cells play an essential part in developing the nervous system, the survival and metabolic support of neurons, and the interaction between cells that regulate signal transmission and plasticity. (Zuchero and Barres, 2015).

## Sensory-motor integration

The nervous system has three principal and overlapping functions: sensory (afferent) input, integration and motor (efferent) output. Sense organs or receptors reactions are based on sensory information or stimuli from both the general and special senses. The energy of the stimulus is translated and becomes nerve impulses. (Per Brodal, 2010) For example, if someone taps your shoulder, the sensory receptors on the skin detects the touch of a hand; that information is called sensory input. Interneurons processes that input and decides the response in a process called integration. The motor output activates the body by sending directions from the nervous system to effector organs such as muscles and glands (Mancall, Brock and Gray, 2011). The motor division includes the voluntary (somatic) nervous system that rules the skeletal muscle movement and the involuntary (autonomic) nervous system (Crossman, Neary and Crossman, 2019) .

# Figures

# References

BJERKNES, T. L. & MOSER, M. 2019. A sense of place. Biologist, 66, p. 10-13.

BRODAL, P. 2010a. 6. Parts of the Nervous System. The Central Nervous System: Structure and Function. New York: Oxford University Press.

BRODAL, P. 2010b. Introduction. The Central Nervous System: Structure and Function. New York: Oxford University Press.

CAREY, J. 2018. Brain facts. A primer on the brain and nervous system. 2018 ed.

CROSSMAN, A. R. & NEARY, D. 2014. Neuroanatomy E-book: an illustrated colour text, Elsevier Health Sciences.

DJEBBARA, Z. 2020. Expecting space: an enactive and active inference approach to transitions.

MANCALL, E. L., BROCK, D. G., 2011. Gray's clinical neuroanatomy: the anatomic basis for clinical neuroscience, ELSEVIER INDIA.

HYDER, F., ROTHMAN, D. L. & BENNETT, M. R. 2013. Cortical energy demands of signaling and nonsignaling components in brain are conserved across mammalian species and activity levels. Proceedings of the National Academy of Sciences, 110, 3549-3554.

IMOTIONS 2019. Electroencephalography - The Complete Pocket Guide. iMotions.

JANSEN, J. & GLOVER, J. 2020. Synapse [Online]. Store medisinske leksikon. Available: https://sml.snl.no/synapse [Accessed April 3rd 2021].

KAPALKA, G. M. 2010. Chapter 3 - Pharmacodynamics. In: KAPALKA, G. M. Nutritional and Herbal Therapies for Children and Adolescents. San Diego: Academic Press.

LA ROSA, C., PAROLISI, R. & BONFANTI, L. 2020. Brain structural plasticity: from adult neurogenesis to immature neurons. Frontiers in neuroscience, 14, 75.

MAGRASSI, L., LETO, K. & ROSSI, F. 2013. Lifespan of neurons is uncoupled from organismal lifespan. Proceedings of the National Academy of Sciences, 110, 4374-4379.

MANCALL, E. L. & BROCK, D. G. 2011. Overview of the Organization of the Nervous System. Gray's Clinical Neuroanatomy: The anatomic basis for clinical neuroscience Elsevier Health Sciences.

REA, P. 2015. Chapter 1 - Introduction to the Nervous System. In: REA, P. Essential Clinical Anatomy of the Nervous System. San Diego: Academic Press.

VON BARTHELD, C. S., BAHNEY, J. & HERCULANO- HOUZEL, S. 2016. The search for true numbers of neurons and glial cells in the human brain: a review of 150 years of cell counting. Journal of Comparative Neurology, 524, 3865-3895.

# 6. Assessing the Quality of Research

Recently there has been raised concerns across several fields of science regarding the accuracy of research findings, and some suggest that ongoing reproducibility crisis. A survey conducted by Nature in 2016 involved 1,576 researchers who participated in an online questionnaire about reproducibility in research (Baker, 2016). The results concluded that more than 70% of researchers had unsuccessfully tried to reproduce another investigator experiment. 90 % of the participants thought there was a slight or significant reproducibility crisis, and only 3 % believed there was no crisis.
There is, however, an ongoing disagreement between researchers about the severity of this ‘crises’. Some claim that most research papers present false results (Ioannidis, 2005, Smaldino and McElreath, 2016),, whiles others argue that this statement is either untrue or yet to be proven (Goodman and Greenland, 2007). Fanelli, on the other hand, argues that “’he new ‘science is in crisis’ narrative is not only empirically unsupported but also quite obviously counterproductive’ (2018). The author refers to similar beliefs that have recurred throughout history and continue by claiming that such statements spread discouragement among the next generations of researchers, who should instead be motivated to produce higher quality research.

<u>Transparency and reproducibility</u>
Transparency and reproducibility are essential in current and future science research (Begley and Ioannidis, 2015). Selective and inadequate reporting as well as selective analysis of conditions limits transparency in research. The ability to replicate findings ensures transparency and provides an understanding of how the original study has been conducted. A study in the field of psychology examined the replications of 100 experimental and correlational studies to determine to what extent reproducibility defines current research. The investigators argues that there is a need for high-powered replications of prominent effects and the research concluded that “a large portion of replications produced weaker evidence for the original findings despite using materials provided by the original authors, review in advance for methodological fidelity, and high statistical power to detect the original effect sizes” (Collaboration, 2015).

<u>Sample Size</u>
An adequate sample size is crucial to the avoidance of research errors. Sample size calculations are performed to ensure that research projects are sufficiently powered and decrease the likelihood of type II errors (false negatives). Systematic reviews from different disciplines do, however, reveal that underpowered studies continue to be published. A systematic review involving 100 randomly selected ERP/EEG articles revealed that 0 of 100 articles reported sample size calculations or provided necessary material for future sample size calculations (Larson and Carbine, 2017). This lack of data questions the studies ability to produce valid results.

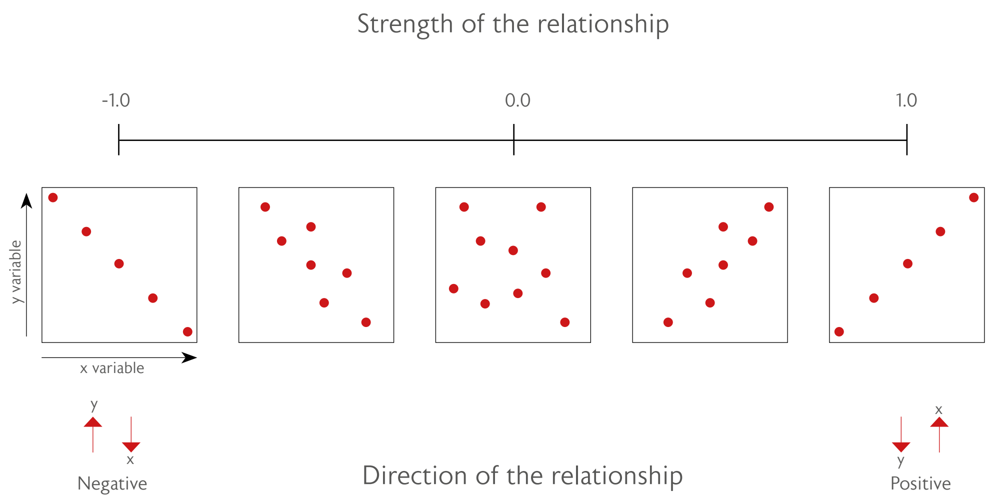



Figure 1 - Correlation coefficients.

The authors argue that there are several reasons why researchers choose small sample sizes. Conducting comprehensive studies requires generous amounts of resources, time, which can cause researchers to select smaller sample sizes. Investigators might also be motivated by personal gain and recognition to speed up the research process, as published studies can lead to new career opportunities.

Bigger is, however, not always better. Too large sample sizes can also cause problems resulting in sampling errors and inaccurate and lacking information. In some cases, big data can even enlarge the bias. Representativeness is generally more important than big data and large sample sizes. A group of participant that does not represent the population can cause misleading results (Kaplan et al., 2014).

### Probability and Effect Size

Conducting comprehensive studies can be both time-consuming, costly and requires a lot of hard work. Generous amounts of recourses are invested into research projects, and, understandably, investigators hope for significant findings (Larson and Carbine, 2017). Data can, however, be manipulated; “if you torture your data long enough, they will tell you whatever you want to hear” (Mills, 1993, p. 1196). Honest exploratory studies should document the number of comparisons, as multiple comparisons can result in false statistically significant findings. In all statistical tests, there is a chance of a false positive (type I error) result (Mills, 1993). The statistically significant threshold usually is 0.05, but when running multiple tests, the I error increases (Sainani, 2009).

P-values illustrates how likely a finding occurs due to chance (Mills, 1993). Eva Skovlund, professor of medical statistics, argues that a p-value cannot be calculated without a specified question. She continues by suggesting an implementation process; 1) ask a question, 2) determine the significance level, 3) formulate the null hypothesis and an alternative hypothesis, 4) perform the experiment, 6) compare the p-value and the significance level, discard null hypothesis if $p < 0.05$. Post hoc data analysis and significance tests pursued due to unexpected observations should be clearly stated in the study, as the p-value is less reliable (Skovlund, 2013).

## Terminology

**Mean value:** Symbol μ. The sum of the sample items divided by the sample size.

**Standard deviation (SD)**: Symbol σ. The variability within a sample.

**Standard error of mean (SEM)**: How far the sample mean is likely to be from the true mean. $\sigma/\sqrt{n}$.

**Effect size:** The magnitude of the difference between groups.

**Null hypothesis:** There is no difference between the two variables that is being studied.

**Alternative hypothesis**: The null hypothesis is not true, even if the results shows

**Correlation coefficients:** A statistical measure of the strength of the relationship and the direction of the relationship of two variables. The values range between -1.0 (perfect negative correlation) and 1.0 (perfect positive correlation), any value grater or lower is regarded as an error in the correlation measurement. 0.0 correlation indicates that there is no linear relationship between the movement of the two variables.

**Confidence intervals:** provides information about the accuracy of an estimate and the probable values of a measure within the test group. A 95 percent confidence interval suggests that if the same study was done 100 times, with participants from the same population pool, 95 of the 100 confidence intervals would contain whatever being estimated. (Mills, 1993)

**Pearson's correlation (Pearson Product Moment Correlation (PPMC):** Symbol r. A measure of the strength and direction of the linear relationship between two variables. It cannot show nonlinear relationships between two variables, nor can it differentiate between dependent and independent variables.

**Statistical Power:** A hypothesis test is the probability of detecting an effect if there is a true effect present to detect.

**Low statistical power:** large risk of committing Type II errors (false negative)

**High statistical power:** small risk of committing Type II errors

**Type I error:** reject the null hypothesis when there is no significant effect (false positive)

**Type II error:** not reject the null hypothesis when there is a significant effect (false negative)

## Figures

# References


BEGLEY, C. G. & IOANNIDIS, J. P. A. 2015. Reproducibility in Science. Circulation Research, 116, 116-126.

COLLABORATION, O. S. 2015. Estimating the reproducibility of psychological science. Science, 349.

FANELLI, D. 2018. Opinion: Is science really facing a reproducibility crisis, and do we need it to? Proceedings of the National Academy of Sciences, 115, 2628-2631.

GOODMAN, S. & GREENLAND, S. 2007. Why Most Published Research Findings Are False: Problems in the Analysis. PLOS Medicine, 4, e168.

IOANNIDIS, J. P. 2005. Why most published research findings are false. PLoS medicine, 2, e124.

KAPLAN, R. M., CHAMBERS, D. A. & GLASGOW, R. E. 2014. Big data and large sample size: a cautionary note on the potential for bias. Clinical and translational science, 7, 342-346.

LARSON, M. J. & CARBINE, K. A. 2017. Sample size calculations in human electrophysiology (EEG and ERP) studies: A systematic review and recommendations for increased rigor. International Journal of Psychophysiology, 111, 33-41.

MILLS, J. L. 1993. Data Torturing. New England Journal of Medicine, 329, 1196-1199.

SAINANI, K. L. 2009. The Problem of Multiple Testing. PM&R, 1, 1098-1103.

SKOVLUND, E. 2013. [Ask first, then count]. Tidsskr Nor Laegeforen, 133, 10.

SMALDINO, P. E. & MCELREATH, R. 2016. The natural selection of bad science. Royal Society open science, 3, 160384.

# 7. Systematic Review

## Aim

In this systematic review I will analyse the results of research that has been done in the field of neuroarchitecture. I will focus on studies that have been done in interior spaces where data has been collected by using objective measurements and subjective assessments. The aim of this systematic review is to get a better understanding of the amount and quality of studies that has been done so far. Additionally I will analyse if variables such as virtual reality vs. reality, vision vs. multi-sensory and participant characteristics, affect the results.

## Review Questions

*Do the theories and methodologies used in the studies correlate and provide trustworthy and comparable results?*

*Are the results from the subjective assessments and objective measurements corresponding and can an overall pattern be detected between the reviewed studies?*

*What are the contributions of theses studies and how can they improve further research in this field?*

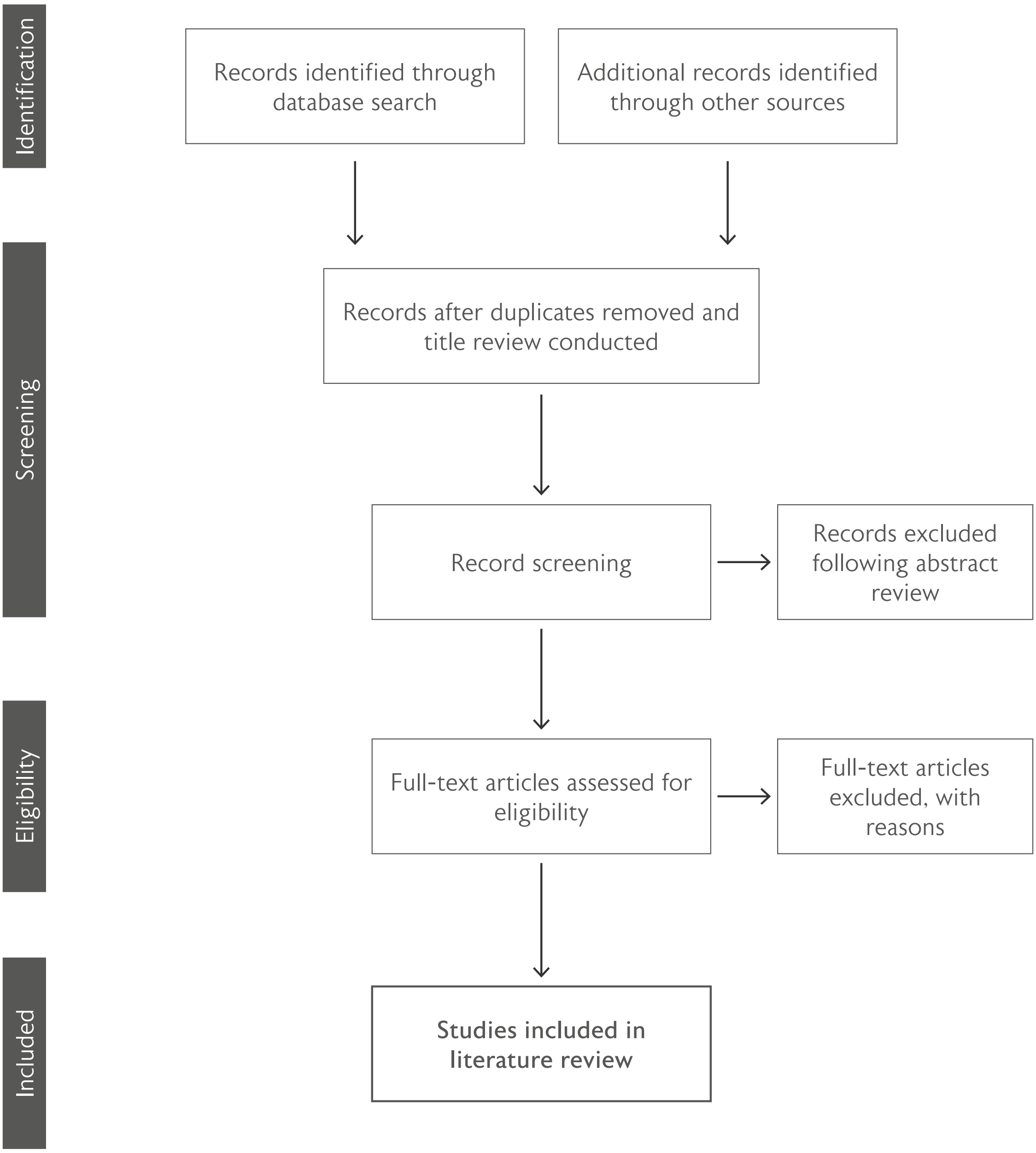



Figure 1 - Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) process.

## Material and Methodology

A systematic literature review was performed to identify studies that are relevant to the topic, as well as to determine the prospects of further research. An iterative systematic approach was to assess the importance of specific criteria. This helped to define words that was used in the literature search and distinguish relevant material.

The strategies guiding the literature search reporting was based on previously published systematic reviews. The number of systematic reviews in the field of neuroarchitecture is limited and search strategies from systematic reviews in adjacent fields was therefore also be included. The PRISMA approach was used as a reporting method. Electronic databases was carefully selected based on relevance and the reference management system Endnote 20 will be used as a reference tool throughout the thesis.

# The emotional impact of built interior environments objectively measured by electrical activity (EEG) and by subjective assessments: A systematic review

## Abstract

B**ackground:** The correlation between human behaviour and the built environments has been studied by architects, philosophers, and social scientists since the 20th century. The field of neuroarchitecture allows architects, psychologists, neuroscientists, and other disciplines to work together and study the short- and long-term cognitive and emotional impact of architectural spaces. Newly developed technologies and methodologies in neuroscience can now prove the accuracy of theories that have earlier only been based on assumptions. The huge array of different scientific approaches that are used today highlights an imminent need to develop standards, cross-validated protocols, and guidelines to improve the quality, reproducibility, and thus the reliability of future research.

**Aims:** Few reviews have previously systematically examined the research- and analytical methods that are being used in this research field. This systematic review aims to evaluate the current body of research done in the field of neuroarchitecture with a focus on the amount of high quality and reliable studies that are currently available.
Methods: The review focuses on existing studies that include interior spaces and data from objective measurements and subjective assessments. An initial search through six databases identified 364 research articles. Of these, 19 met the abstract selection criteria, and one study met the full-text selection criteria. Three articles that I previously was aware of were added and one additional article was identified from background and foreground citation chasing. In total, only five studies met the criteria for Inclusion. Most studies were excluded due to vast differences in methodological approaches and test environments.

**Results:** Even if none of the studies had a setup that made it comparable to the others, the results from the subjective assessments and the EEG recordings in all studies demonstrate that the built environment affects us both emotionally and physically. The review finds that various monitor systems should be used simultaneously during experiments as recordings of both brain activity and physical responses will increase the reliability of data recording. Emotions are subjective and complex, and conducting trustworthy studies requires objective techniques, subjective assessment, and a multidisciplinary approach. The reviewed studies are valuable as they lay an essential groundwork for further studies to build on.

**Conclusions:** By using a neuroarchitectural approach, the identification of environmental stressors that affect human mental and physical health, will support architects in making design choices that have a positive impact on the built environment. Further research based on international standardisation of methodology and the use of well-designed studies is highly needed.

## 1. Introduction

In a world where we spend most of our time indoors, and climate changes and social issues have become a frightening reality, we can no longer afford to waste resources on unsustainable architecture. Humans need to constantly adapt to the built environment and all multisensory stimuli it entails. Neuroarchitecture can potentially give scientific insight into human response patterns in built environments. Such findings can inform architects during the design process and consequently positively impact the future of the built environment. Better knowledge about humans' cognitive and emotional responses to the built environments could be used to improve inhabitants' physical and mental health. Additionally, it may result in more efficient use of space with a beneficial impact on the building's functionality, quality, sustainability, and the economy.

This systematic review aims to evaluate the current body of research in the field of neuroarchitecture. The review will focus on existing studies that include interior spaces and data from objective measurements and subjective assessments. The aim is to gain a better understanding of the amount and quality of studies that are currently available. Additionally, I will evaluate if virtual reality vs. reality, vision vs. multiple senses, and participant characteristics affect the results. To my knowledge (see Appendix B, P. 124), no previous review has evaluated the research- and analytical methods of similar studies to this extent.

### 1.1. Background

People spend most of their time surrounded by the built environment, from birth throughout life and ultimately death. Research shows that Europeans spend almost 22 hours a day indoors (World Health Organization regional office for Europe, 2013). Cities are continuously growing, and two-thirds of the world's population will live in urban areas by 2050. Consequently, the urban area will expand significantly to provide shelter and facilities for the 2.4 billion new inhabitants (Goldhagen and Gallo, 2017, United Nations Department of Economic and Social Affairs, 2018). Therefore, it has never been more critical than now to create sustainable built environments that promote good health and well-being.

Since the dawn of human dwelling, intuition has been a key in creating environments where humanity can prosper. Theories about the relationship between 'the mind and the body' and 'the body and space', and the connections between architecture and anatomy, physiology, psychology, phenomenology, and intuition, have historically been of great human interest. The term 'architectural determinism' was first used by the British planner Maurice Broady. In the article, 'The Social Context Of Urban Planning' (1969) Broday claims that the built environment can predict and determine social behaviour. Few professionals have since adopted this somewhat controversial idea, but many architects have voiced beliefs that architecture can affect human behaviour and wellbeing.

Subjective experiences and intuitive judgment have traditionally supported architectural theories and decisions. However, the development of research methods and technology has made it possible to incorporate scientific evidence in the architectural decision-making process. Architects and psychologist have, through empirical research, studied the correlation between human behaviour and the build environments since the 20th century (De Paiva and Jedon, 2019). Experience-based research uses assumptions to make conclusions regarding human behaviour, but not evidence-based data from experimental studies. The field of neuroarchitecture allows architects, psychologists, neuroscientists, and other disciplines to work together and investigate the short- and long-term cognitive and emotional impact of architectural spaces.

## 1.2. Neuroarchitecture

The brain has been described as "the most complex thing in the universe" (Pacitti et al., 2019) and it is intricate in both structure and function. Traditionally, the term 'neuroarchitecture' was used in neuroscience to describe the brain's form and function (Eberhard, 2009). The expression has been adopted by architects and neuroscientists and is now used to describe a multidisciplinary research field in which the relationship between the human brain and the built environment is studied (Azzazy et al., 2020). Neuroarchitecture thus connects the fields of neuroscience and architecture. Studies based on measurable neurological findings are relatively new, and the field of neuroarchitecture is rapidly evolving as new diagnostic methods develop. This opens up for new research and many intriguing hypotheses are yet to be tested.

## 1.3 Neuroarchitectural Methods

The brain and the nervous systems function have fascinated scientists and clinicians all over the world for many years. Neuroscience is multidisciplinary and includes a variety of scientific fields, such as biology, genetics, medicine, psychology, chemistry, computer science, engineering, and mathematics. During recent years many discoveries and advances have been made due to the rapid progress and increase of technology (Kaiser, 2014). New scientific findings have provided a greater understanding of human psychological and behavioural needs and the functions of the pathological nervous system. The Society for Neuroscience predicts that this rapid growth will continue during the next 50 years, and new advances can improve human health, the economy, and society (Altimus et al., 2020).

Substantial amounts of recourses have been granted to the field of neuroscience in the quest to get a better understanding of human behaviour, experience, and related diseases. Neuroscience is currently one of the most active areas of contemporary biology and medicine (Mancall and Brock, 2011). The new scientific advances have caught both scientists and the general public's attention. New discoveries have contributed to a better understanding of the organisation and function of the brain and consequently the treatment of mental and neurological disorders (Quaglio et al., 2017). The development of functional imaging techniques, processor technologies, data analysis procedures, and algorithms have allowed researchers to investigate the brain functions in greater detail (iMotions, 2019). There are a variety of functional imaging techniques available, which are used for scientific, medical, educational and commercial purposes (see Table 1).

### 1.3.1. Electroencephalogram (EEG)

In recent years there has been a rapid development of EEG equipment due to new and innovative digital technology. Today, EEG is a widely used method to analyse brain function in research and to diagnose medical conditions such as epilepsy and sleep disorders (Da Silva, 2009). EEG equipment has become a popular tool as it is relatively inexpensive, is mobile, and is relatively easy to use.

EEG offers continuous recording of brain activity by measuring the differences in voltage (electrical potential) between two electrodes. It is a non-intrusive method where electrodes are attached to the scalp. Modern EEG has a millisecond temporal resolution, and this means that it can produce thousands of images per second of the electrical activity from multiple electrodes. A disadvantage with EEG is its poor spatial resolution. The electrodes record the electrical activity from the scalp (surface) and cannot determine the exact source of the activity. However, advances in EEG acquisition systems and electric head modelling (3D models showing in which parts of the brain the activity takes place) have improved the spatial resolution of scalp EEG (Ferree et al., 2001). High-density EEG recording (64 - 256 channels) offers a higher number of solution points and therefore more spatial resolution, and somewhat better spatial accuracy. The accuracy, however, stops improving when the solution points exceed a certain number as the number of electrodes that are possible to attach to the skull limits the quantity of input (Michel and Brunet, 2019).

The number of electrodes varies from 10 to several hundred, depending on the equipment and the size of the experiment. Several factors affect the price and accuracy of the EEG equipment. More expensive equipment usually has more electrodes, advanced digitalising software and an amplifier

| Implicit Technique | Measure's: | Temporal resolution | Spatial resolution | Neural signal | Invasive | Test setting | Training | Cost | Mobility |
|---|---|---|---|---|---|---|---|---|---|
| fMRI | Function (Metabolic) | Low (~1s) | High | Indirect | No | Research/ clinical | Extensive | High | Stationary |
| PET | Function (Metabolic) | Low (≥10s) | High | Indirect | Yes | Primary clinical | Extensive | High | Stationary |
| EEG | Function (Electrical) | High (1-4ms) | Low | Direct | No | Flexible | Some | Low | Stationary/ portable |
| MEG | Function (Magnetic) | High (1-4ms) | High | Direct | No | Research/ clinical | Extensive | High | Stationary |

Table 1 - Common functional brain imaging techniques.
Adapted from iMotions, 2019, Koike et al., 2013, McLoughlin et al., 2014

fMRI = Functional magnetic resonance imaging
PET = Positron emission tomography
EEG = Electroencephalogram
MEG = Magnetoencephalography

| System (brand) | Channels | Electrode type | Resolution (bits) | Maximum sampling rate (Hz) | Bandwidth (Hz) | Weight (g) | Battery life (h) | Mobility |
|---|---|---|---|---|---|---|---|---|
| EPOC (Emotiv) | 14 | Wet (saline) | 14-16 | 128/256 | 0.16-43 | 116 | 6-12 | Mobile |
| B-Alert x10 (Advanced Brain Monitoring) | 9 (+1 optional) | Wet (gel) | 16 | 256 | 0.1 | 71 | 10.5 - 12.5 | Mobile |
| BEMicro, EB-Neuro | 24 | - | - | 256 | - | - | - | - |

Table 2 - EEG systems.
* EBNeuro is a portable recording device for EEG monitoring.

with higher sampling rates (Abreu et al., 2018, iMotions, 2019).
A range of technology and equipment is necessary to record reliable EEG data, including devices to deliver stimuli, an EEG headset to record brain activity, an EEG amplifier, and a computer to amplify, filter, and convert analogue electrical signals from the sensor into digital signals. The electrode that captures brainwave activity is called an EEG channel, and the number of channels determines the density (more detailed information) of the EEG recording.
Artefacts in EEG are signals recorded by EEG but not generated by the brain. EEG data can become affected by a variety of different artefacts that originate from internal and external sources. Internal sources of artefacts are caused by physiological activity and movement, while external sources of artefacts are due to environmental interferences, the recording equipment, electrode popping and cable movement. (Islam et al., 2016).

## 2. Method

### 2.1. Search strategy

The strategy that I have used for the literature search reporting is based on previously published systematic reviews. The number of systematic reviews in neuroarchitecture is limited, and search strategies from systematic reviews in adjacent research fields were therefore also included (Borgianni and Maccioni, 2020, Bower et al., 2019, Button et al., 2013, Norwood et al., 2019). The PRISMA approach (Moher et al., 2009) was used as reporting guidelines and the newly published extensions, PRISMA -S (Rethlefsen et al., 2021) and PRISMA 2020 (Page et al., 2021) were also taken into consideration.

### 2.2. Study Identification

The following six electronic databases were carefully selected; Scopus, MEDLINE, Web of Science Collection, APA PsycInfo, CINAHL and Psychology and Behavioral Sciences Collection (Gusenbauer and Haddaway, 2020, Rethlefsen et al., 2021), and searched for peer-reviewed literature. The comprehensive literature search for the six databases was run on 29 March 2021. The following search words were added: (Electroencephalography* OR EEG* OR (Event-related potential) OR ERP OR (brain oscillation) OR (brain activity) OR (brain response) OR (cerebral activity) OR (Physiological response) OR (Neurophysiological response)) AND (built OR space OR (physical environment) OR (spatial environment) OR (virtual environment) OR environment* OR (architectural space) OR architecture* OR neuroarchitecture). Table 3 shows an overview of each

| Platform | Database | Date | Search | Findings |
|---|---|---|---|---|
| PubMed | MEDLINE | 29.03.2021 | Title | 130 |
| Scopus | Scopus (Full index) | 29.03.2021 | Title | 395 |
| Web of Science | Web of Science Core Collection | 29.03.2021 | Title | 265 |
| EBSCOhost | Psychology and Behavioral Sciences Collection | 29.03.2021 | Title | 8 |
| EBSCOhost | CINAHL | 29.03.2021 | Title | 22 |
| PsycARTICLES | APA PsycInfo | 29.03.2021 | Title | 70 |
| Total | | | | 890 |

Table 3 - Information from initial database search.

database search.

Asterisk (*): Indicates a search of the root of the word as well as alternate endings.
Brackets ( ): Indicate phrase searching.
Some of the databases use different symbols and the search was adapted accordingly.

Some journal articles that I found during my studies of the subject were not identified by the search engines. This was despite the fact that they were compatible with the search criteria and these articles were therefore also included. A forward and backward search was then conducted based on all the selected articles (see Appendix B, p. 114-117). The reference list of each included article was manually screened to identify additional studies. Google Scholar was used to perform the forward citation search. The citations were manually added to EndNote 20, then the inclusion criteria (see 2.3. Inclusion criteria) were applied, and the screening was conducted (see 2.4. Screening and study selection).

## 2.3. Inclusion criteria

The following search limits were applied by adding search filters to the initial database search: (1) The English language. (2) Articles available in full version. (3) Journal articles published from 2010 to 2020. The research field of Neuroarchitecture is relatively new and consequently rapidly evolving. Studies published during the last decade were therefore considered to best reflect the current understanding of the thematic. (4) The search was limited to peer reviewed and published journal articles to ensure quality and relevance. Excluded publication types included conference papers, bachelor theses, master theses, PhD theses, book chapters and literature reviews.

## 2.4. Screening and study selection

The articles were screened in four steps: (1) Duplicates were removed both by using the reference management system Endnote 20's duplicate identification strategy (NTNU, 2021) and then double-checked manually. (2) Titles that did not fit with the preselected limitations were excluded. (3) Abstracts that did not fit with the preselected limitations were excluded. (4) Articles in full text that did not fit with the preselected limitations were excluded. A final filtration was conducted after the citation chasing and additionally seven studies were excluded due to a lack of homogeneity. This was done to ensure that the included studies could be compared and assessed.

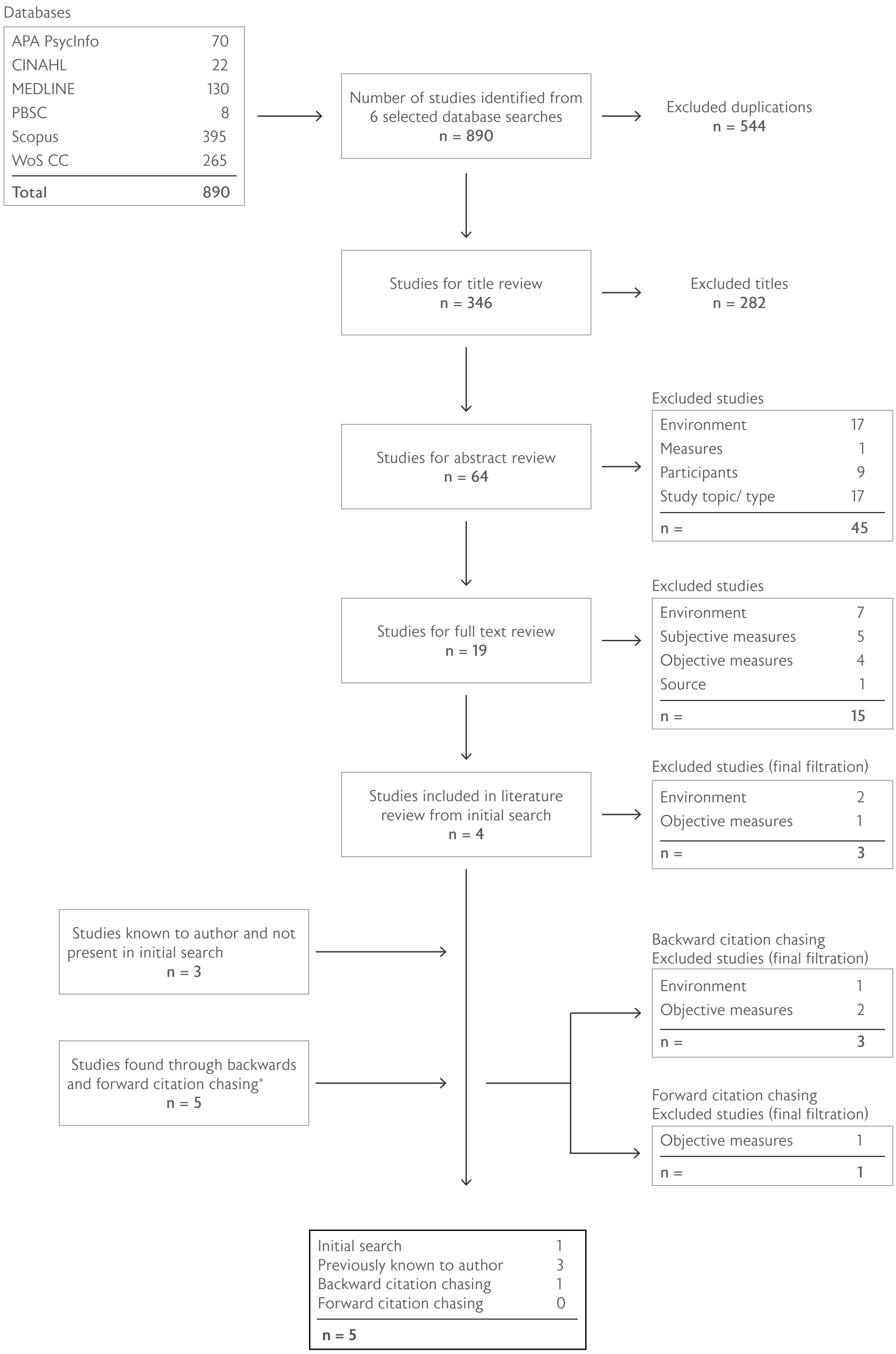



Figure 2 - PRISMA flow diagram illustrating the screening process.

* Citation chasing was conducted by reviewing the reference lists from each of the seven selected studies (backwards citation chasing) and by using Google Scholar (forward citation chasing).

The PRISMA flow diagram (see Figure 2, p. 64) illustrates the screening process. More detailed information about the screening process and study selection can be found in the supplementary material (Appendix A: Supplementary material).

## 2.5. Data extraction and study selection

The studies were selected by the following criteria: (1) Study topic (must be of relevance to the topic of the review). (2) Study type (journal article). (3) Environment (laboratory, naturalistic, natural). (4) Participants (healthy adults). (5) Conditions (indoor). (6) Subjective measures (surveys, questioners, self-report scale) (7) Objective measures (electro encephalography: EEG) (8) Source (published article in a journal with high impact factor in the field of neuro architecture*). (9) Outcomes (e.g., EEG results and, subjective score). (10) Peer reviewed. The process is illustrated in the PRISMA flow diagram (see Figure 2, p. 64).

* The impact factor illustrates the citation rate of articles in regard to the number of citable articles, Neuroarchitecture is a narrow scientific field which affects related journals impact factor. The journals impact factor was therefore judged based on the comparative score of journals in the same field.

## 2.6. Methodology quality assessment

An assessment of methodological quality was guided by a quantitative version of the McMasters rating tool (Law et al., 1998a) that is often used to evaluate quantitative studies within systematic reviews (Norwood et al., 2019, Lakhani et al., 2019, Lakhani et al., 2017, Yost et al., 2014, Louw et al., 2011). The McMasters rating tool is used to ensure the quality of evidence for each study outcome and will thereby also secure the quality of the results in this systematic review by categorising and evaluating the presence and absence of key aspects. The studies selected to be reviewed were evaluated and rated based on study and sampling methods, data collection and analysis, conclusions, and overall rigour. The quantitative studies review form is divided into eight overarching headings, including (1) Study Purpose, (2) Literature, (3) Study Design, (4) Sampling, (5) Data Collection, (6) Data Analysis, (7) Overall Rigour, (8) Conclusions & Implications. The answer options for the underlying 14 domains are divided into 1 and 0, where 1 represents 'yes' and 0 represents 'no', 'not appliable 'or 'not addressed' (see table 12, p. 78).

## 3. Results

Nineteen papers from the initial database search met eligibility in the title and abstract review. The number of qualified studies was narrowed down to four through the full-text screening. Three additional studies, pre-known to the author but not present in the initial database search, were also added. A forward and backward citation searching of the seven eligible studies resulted in four additional studies. A final independent full-text screening resulted in a removal of six studies, and as a result, five studies were ultimately included in the review. The screening process is detailed in Figure 2. The five studies that met the search criteria and were included in this review are described below. (See Appendix A for complete screening process and characteristics of studies).

### 3.1. Clarifications

The results are presented in a series of tables to clarify the similarities and differences between the studies. However, the results from the natural outdoor environment will not be considered as it does not fit the reviews inclusion criteria (see 3.2 Characteristics of the studies). The subsections below refer to data from the studies main experiment, and it is clearly stated when data from multiple experiments are mentioned.
The words 'study', 'trial' and 'experiment' are used frequently throughout the text. Therefore, it is beneficial for the reader to know how these terms are used in this review: Five studies fit the inclusion criteria. Each study includes experiments in which the researchers' hypotheses are tested during trials. Hence, each participant partakes in one main experiment that involves several trials with different test variables.

### 3.2. Characteristics of the studies

The five studies included in this review met the inclusion criteria described above (see 2. Method). Study (iv) was included, even If it contained an exterior scenario as two interior scenarios in the study fitted the inclusion criteria. The results from the two included scenarios (interior spaces) were independent and not affected by the result from the excluded scenario (exterior space).

In the following paragraphs, the studies are referred to as the Roman numerals listed below:

i. Walking through Architectural Spaces: The Impact of Interior Forms on Human Brain Dynamics (Banaei et al., 2017b)

ii. Quantifying Human Experience in Architectural Spaces with Integrated Virtual Reality and Body Sensor Networks (Ergan et al., 2019)

iii. Multisensory stress reduction: a neuro-architecture study of paediatric waiting rooms (Higuera-Trujillo et al., 2020)

iv. Building environment information and human perceptual feedback collected through a combined virtual reality (VR) and electroencephalogram (EEG) method (Li et al., 2020)

v. Electroencephalographic Correlates of Sensorimotor Integration and Embodiment during the Appreciation of Virtual Architectural Environments (Vecchiato et al., 2015)

### 3.2.1. Participants

All five selected studies reported that healthy adults participated in the experiments. In general, the research articles provide very little detailed information about the participant's demographic characteristics, age, gender, general health, and recruitment criteria. Study (ii) and (iii) did report that participants were asked to fill out a demographics survey, while study (iv) only informed that basic personal information was collected from each participant. The data from the demographic surveys were, however, not disclosed in the research articles.

<u>Recruitment criteria</u>
Study (ii) did not enclose any recruitment criteria but merely stated that a large pool of participants was invited to participate in the experiments. Generic information about the participant's health was included in Study (iii), identifying them as physically and mentally healthy with no recent significant illnesses. Study (i, iv and v) specified that the participants had 'normal or corrected-to-normal vision'. Four studies had additional and specific selection criteria: Study (i) participants must be right-handed with no prior education in architecture or history of neurological diseases, Study (iii) the participants children must be users of the paediatric service and not suffer from any condition with contraindications for the use of virtual reality technologies, Study (iv) participants must be students (Li et al., 2020) and Study (v) participants should not be familiar with Immersive Virtual Reality (IVR). None of the research articles specified what the

| | Participants | Mean Age | Objective measurements | Subjective assessment | Investigation |
|---|---|---|---|---|---|
| i. | 15 (8f + 7m) | 28.6 | EEG | SAM test | Interior forms cognitive and affective impact on humans |
| ii. | 32 (11f + 22m) | NR* | EEG | Self-report survey | Architectural design features impact on human's stress and anxiety levels |
| iii. | 24 (11f + 13m) | 37 | EEG | Self-report assessment | Design characteristics effect on stress reduction |
| iv. | 30 (15f + 15m) | NR** | EEG | Questionnaire | Interior spaces cognitive and emotional impact on humans |
| v. | 17 (5f + 12m) | 26.8 | EEG | Questionnaire | Interior furnishings styles effect on people's cognitive and emotional states |

Table 4 - Characteristics of the selected studies.

(i) Banaei et al., 2017, (ii) Ergan et al., 2019, (iii) Higuera-Trujillo et al., 2020, (iv) Li et al., 2020, (v) Vecchiato et al., 2015.

f = female
m = male
NR = Not reported
EEG = Electroencephalogram

* Age range between 21 and 30 years old
** Age range between 18 and 25 years old

| | Physical environment | Setting | VR devices | VR software | Individual variables |
|---|---|---|---|---|---|
| i. | Laboratory | VR | Head-mounted VR display (HTC Vive) and HMD controller | Unity game engine software | Interior spaces with different architectural forms |
| ii. | NR | VE | Touch screen, Apex controller (Vicon Motion Systems) and 3D goggles | Unity game engine software | Environments with different luminance, daylight, colour surfaces, outside view |
| iii. | Controlled laboratory environment | VR | Head-mounted VR display (HTC Vive) | NR | Replicas of paediatric waiting rooms with different visual, auditory and olfactory |
| iv. | Controlled laboratory environment (LEC) | VR | VR helmet | Unity game engine software | Natural, semi-open, and closed spaces |
| v. | Laboratory | VE | Viewsonic projectors using Nvidia 3D vision wireless glass | CAVE system | Bedrooms with different furniture |

Table 5 - Physical and virtual environment.

(i) Banaei et al., 2017, (ii) Ergan et al., 2019, (iii) Higuera-Trujillo et al., 2020, (iv) Li et al., 2020, (v) Vecchiato et al., 2015.

NR = Not reported
VE = Virtual Environment
VR = Virtual reality

recruitment criteria entailed (e.g., what is considered to be physically and mentally healthy?) or how the researchers concluded that a recruitment criterion was achieved (e.g. was the participant's vision tested?).

Age

In total, there were 118 participants in the five studies, all 18 years of age or older. The participant's age was significantly higher in Study (iii), with a mean age of 37 years, compared to the other four studies with most participants in their twenties. Study (i, iii and v) reported the mean age of the participants and the standard deviation, while Study (ii and iv) reported the participant's age range. None of the research articles included both the participants mean age, age-range, and information about each individual's age.

Gender

The gender mix varied among all the studies: only Study (iv) reported an equal number of male and female participants. Study (i) had an odd number of participants with one more female, and Study (iii) had an even number of participants with two more male. Study (ii and v) had a noticeable gender imbalance with approximately twice as many male as female participants. The reason for this gender imbalance was neither described nor justified in the research articles.

Sample size

The mean number of participants in the five studies was 23.6 (See Appendix B, p. 112 for calculations) with a standard deviation of 6.77 (see Appendix B, p. 111 for calculations). There was no explanation on how the sample size had been determined in Study (i, iii, iv and v). Study (ii) reported that a statistical analysis was conducted, and the effect size calculations concluded that 32 subjects were sufficient to have a 5% significance level using a two-tailed t-test.

### 3.2.2. Laboratory setting

Study (i, iii, iv and v) disclosed that the experiments took place in laboratories, but their geographic locations were not documented. All environments were virtual, but the physical (laboratory) spaces and virtual environments in the different studies fluctuated in size. Auditory (hearing) and olfactory (smell) stimuli were included in addition to visual stimuli in Study (iii and iv).

Environmental conditions

Study (iii and iv) reported that the experiments took place in a controlled laboratory environment. Study (iv) specified monitored conditions including temperature, humidity, carbon dioxide and formaldehyde concentrations.

Figure 3 - Example of two virtual rooms with different geometry and forms that were used in Study (i).

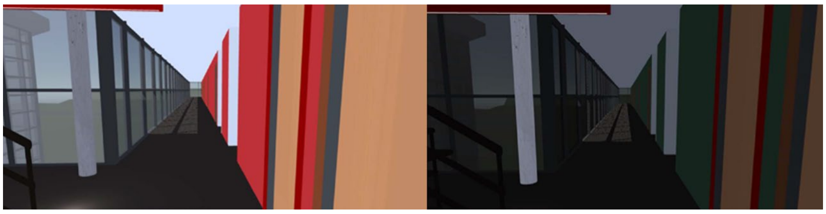


Figure 4 - Images of the visual stimulation that was used in Study (ii).
The first image represents the stress-reducing environment, and the second image represents the stress-inducing environment.

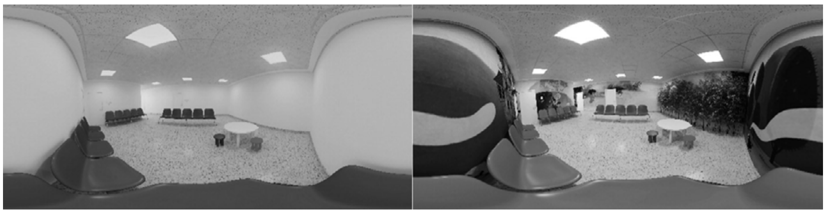


Figure 5 - Images of the visual stimulation that was used in Study (iii).
The first image shows the 'standard waiting room replica' and the second image shows the same room with added vegetation and pictures for children.

Figure 6 - Images of the visual stimulation that was used in Study (iv).
The first image shows the semi-open library space and the second image shows the enclosed study room.

Figure 7 - Images of the visual stimulation that was used in Study (v).
The first image represents the room with 'modern design', and the second image represents the room with 'cutting-edge furniture'.

Virtual reality (VR)
In four studies, the participants used VR headsets to view virtual environments. Study (i and ii) used computer-generated environments and interactive controller devices to navigate. Study (iv) used 360° images of real environments as stimuli, whilst Study (iii) only described the stimuli as replicas of real environments. A virtual reality cave system setup composed of projection screens displaying three-dimensional images of simulated rooms was used in Study (v).

### 3.2.3. Environmental and design variables

Multisensory stimuli
Two studies used multisensory design features during the experiments located in controlled laboratory environments. Study (iv) used an interior semi-open library space and a study room in a basement. In the study different visual and auditory stimuli (lighting, scales, and noise) were applied. The researchers state that the selected spaces (open, semi-open and enclosed space) were based on comprehensive analyses of different image samples. It is, however, not stated what the comprehensive analyses entailed.

Study (iii) used a paediatric waiting room with variations of different visual, auditory, and olfactory stimuli (including vegetation, decoration, noise and scent). In an initial analysis, 20 physical waiting rooms in Spain were used to identify the variables that had the best effect on reducing the participant's stress levels. One hundred and twenty participants assessed 19 environmental satisfaction variables. The researchers then used an affinity diagram to create a digital replica of the waiting rooms used in the following experiments. Four test environments were created with different smells and sounds, and a variation in interior features. Both studies used different multisensory design features during the main experiments while recording the participant's stress levels (see Table 6, p. 72).

Visual stimuli
Three of the studies focused on visual stimuli, but the types of features varied. Study (i) used different interior form features to explore how geometry and form affect the participant's levels of pleasure and arousal. 3D models of the interior spaces were built with white interior colour and identical lighting to eliminate other design variables that could affect the results. A cluster analysis of different form features was first conducted to determine which structures to use and display in the experiments. The cluster analysis was based on the results from a previous study (Banaei et al., 2017a). Data-mining techniques were used to create form clusters (according to forms, geometry, scale, location, and angles) from images

| | Type of stimuli | Emotions being recorded | Virtual test environment | Visual stimuli | Auditory stimuli | Olfactory stimuli |
|---|---|---|---|---|---|---|
| i. | Visual | Pleasure and arousal | Residential interior space | Interior geometric form features | NR | NR |
| ii. | Visual | Stress and anxiety | Educational facility | Lighting (daylight and luminance), wall colours, openness of space and visual cues (entrance and outside view) | NR | NR |
| iii. | Multisensory | Stress | Paediatric waiting room | With/ without vegetation and wall decoration for children | Relaxing music/ hospital ambient noise | Relaxing scent/ hospital simulation scent |
| iv. | Multisensory | Attention, comfort and satisfaction | Semi-open library space/ enclosed study room in basement | Lighting (daylight and artificial light) and, scale and openness of space | People walking and talking | |
| v. | Visual | Familiarity, novelty, comfort, pleasantness, and arousal | Bedroom | Type of furniture | People walking and talking | NR |

Table 6 - Environmental and design variables.

(i) Banaei et al., 2017, (ii) Ergan et al., 2019, (iii) Higuera-Trujillo et al., 2020, (iv) Li et al., 2020, (v) Vecchiato et al., 2015.

NR = Not reported

| | Position | N. environments | Trials and environments per participants | Trial activity | Tasks preformed during experiment |
|---|---|---|---|---|---|
| i. | Walking | 69 (4 rooms x 17 clusters + 1 neutral room) | Environments: 69 Trials: NR* | Walking through interior rooms | (1) Enter the room and walk until reaching the rooms border. (2) Turn 90° to the right and face the right wall. (3) Turn 90° to the left and face the front wall (4) Turn 90° to the left to face the left wall. (5) Turn 90 ° to the left and walk back to the entrance door. (5) Turn 180° to face the room. |
| ii. | Standing | 2 (1 space x 2 versions) | Environments: 2 Trials: 2 | Navigating through virtual environments | (1) Find room A on the 3rd floor of the building. (2) Find the thermostat in that room and check its temperature and adjust it. (3) Find room B to and adjust the temperature of Room A. |
| iii. | Sitting | 4 (1 spaces x 4 versions) | Environments: 4 Trials: 4 | Observing waiting rooms | Sit and wait |
| iv. | Sitting | 2** | Environments: 2 Trials: 2 | Observing a Semi-open and closed space* | Perform: (1) Stroop test. (2) Digital calculations. (3) Meaningless figures recognition. (4) Symbolic digital simulation. |
| v. | Sitting | 3 (1 space x 3 versions) | Environments: 3 Trials: 3 | Observing bedrooms | Visually explore the surrounding environment. |

Table 7 – Procedure.

(i) Banaei et al., 2017, (ii) Ergan et al., 2019, (iii) Higuera-Trujillo et al., 2020, (iv) Li et al., 2020, (v) Vecchiato et al., 2015.

* The number of trials depends on the time the participant spends in each environment, as the total time used per experiment is fixed.
** One space (open outdoor green space) was not included as it does not fit the inclusion criteria (see 3.1 Clarifications).

NR = Not recorded

of living rooms from different style epochs (before 1900, 1900–1950, 1950–2000, and 2000–2016). Data-mining refers to a process of finding patterns from comprehensive amounts of data. In the cluster analysis, the five most prominent features from each cluster were used to build 75 rooms (3 rooms x 25 clusters) and the 17 clusters with the highest SAM test rating score were selected. One extra room was added, in addition to the three previous rooms, which resulted in 68 virtual spaces. Lastly, a plain room with no design features was included, resulting in 69 rooms with different form features (4 rooms x 17 clusters + 1 neutral room).

Like the study using a paediatric waiting room (see Multisensory stimuli above), two other studies used a virtual room, but with various features to create different environments. Study (ii), much like the study with the paediatric waiting room, investigated the correlation between participants stress and anxiety levels and architectural design features.
Two versions of a 3D model, based on a real educational facility, represent a stress-reducing environment and one stress-inducing environment. The stress-reducing environment had plenty of natural daylight, a standard level of luminance, bright interior wall colours, visible exterior landmarks, and an entrance. In contrast, the stress-inducing environment had less daylighting, low levels of luminance, dark interior wall colours and fewer or no outdoor landmarks.

Study (v) aims to show how architecture affects people's cognitive and emotional states. Immersive Virtual Reality (IVR) was used to generate full-scale interior spaces within a controlled environment. Three versions of a virtual bedroom were displayed, and the participant's perception of pleasantness, novelty, familiarity, comfort, arousal, and presence was measured. One of the rooms had no furniture, and another room was described as being equipped with 'modern design' and the last room was equipped with 'cutting-edge furniture'. No explanation (except snapshots of the rooms) was given to demonstrate how these definitions were decided nor what 'modern design' and 'cutting-edge furniture' entailed.

## 3.3. Procedure

### 3.3.1. Control

All studies state that EEG recordings were done at baseline to be used as comparators for the EEG analyses taken during the experiments. Study (i and v) used basic rooms without any design variables to record the participant's brain activity before adding visual stimuli. Study (ii, iii and iv) recorded biometric data pre-experiment while the participants were relaxed, and the recorded data was used as baseline metrics.

| Implicit Technique | Biometric Signal | Sensor | Features |
|---|---|---|---|
| EEG | Changes in electrical brain activity | Electrodes attached on scalp | Frequency band power, functional connectivity, event-related potentials |
| EMG | Electrical activity produced by skeletal muscles | Skin electrodes inserted into the muscle | Muscle response or electrical activity in response to nerve stimulation of muscles |
| PPG | Volumetric variations of blood circulation | A light source and a photodetector | Heart rate estimation and pulse oximetry readings |
| EDA /GSR/SCL | Changes in skin conductance | Electrodes attached to fingers, palms or soles | Skin conductance response, tonic activity and phasic activity |
| HRV | Variance in time between heart contractions | Electrodes attached to chest or limbs or optical sensor attached to a finger, toe or earlobe | Time domain, frequency domain, non-linear domain |

Table 8 - Overview of implicit techniques used in the reviewed studies.

Adapted from Marín-Morales et al., 2020

| | Emotions being recorded | DS | EEG device/ software | System | Density | Other sensors | Subjective assessment | Other psychological tool |
|---|---|---|---|---|---|---|---|---|
| i. | Pleasure and arousal | NR | EASYCAP/ EEGLAB | Wet | 128 channels | NR | SAM test (each trial), 9-point Likert scale (-4 to 4) | Stroop test |
| ii. | Stress and anxiety | YES | EMOTIV, EPOC* | Wet | 14 channels | GSR, EMG and PPG | Self-report survey (after experiment) | NR |
| iii. | Stress | YES | ABM, B-Alert x10/ Motion, EEGLAB | Wet | 9 channels | EDA, HRV | Stress-self assessment and State Anxiety Inventory (each trial) | SUS questionnaire |
| iv. | Attention, comfort and satisfaction | NR | NR** | NR | NR | NR | Face-to-face questionnaire (each trial), 7-point semantic difference scale (-3 to 3) | Cognitive experiments tests |
| v. | Familiarity, novel-ty, comfort, pleasantness and arousal | NR | BEMicro, EBNeuro/ EEGLAB | Wet | 24 channels | EDA, HR, SCL | 2 Verbal questionnaires (each trial) 9-point scoring scale (1 to 9) | NR |

Table 9 - EEG-devices and subjective assessments.

* Device was not stated in research article. Identified by the author of this review from Figure 3(b) in the article.
** The EEG-device was only described as an EEG signal acquisition caps in the research article.

NR = Not recorded
DS = Demographic survey
ABM = Advanced Brain Monitoring
EEG = Electroencephalogram
NR = Not reported
GSR = Galvanic skin response
EMG = Electromyography
PPG = Photoplethysmogram
EDA = Electrodermal activity
HR = Heart Rate
HRV = Heart Rate Variability
SCL = Skin Conductance Level

### 3.3.2. Trials and environments

Four studies used different versions of the same spaces for each trial whereas Study (iv) involved two trials with two independent spaces, a semi-open space and enclosed space. In Study (ii), participants were asked to navigate through two versions of an educational facility where one setting had stress-inducing features and the other had stress-reducing features. A similar procedure was used in two other studies; Study (v), where participants experienced two versions (furniture styles) of the same virtual bedroom and Study (iii), involving four trials with four versions of the same paediatric waiting room. Study (i) differed from the others because each experiment involved a variation of 69 environments and was the only study where all participants did not experience the same environments during the trials.

### 3.3.3. Tasks performed during experiment

The trials in Study (i, ii and iv) involved tasks that had to be completed before the participants could move on to the next trial. Study (iii and v) only required the participants to explore the environments visually. In three studies, the time spent in a trial was determined by the time it took to complete specific instructions and tasks: Study (iv) cognitive tasks, Study (ii) navigating within a space and performing predetermined tasks and Study (i) moving inside a room.

## 3.4 Outcomes

### 3.4.1. Neurophysiological data

EEG was one of the inclusion criteria for the selected studies in this review (see 2. Method). A range of different EEG devices and analysing software's were used across the studies (see Table 9, p. 74). Study (iv) did not report the name of the brand of the EEG equipment or software used, nor the density of channels. The other four studies used wet electrodes (uses an electrolytic gel or liquid as a conductor between the skin and the electrode) but devices from different brands (EASYCAP, BEMicro and EMOTIVE) with different amounts of channels. The number of channels ranges from 9 to 128, and the sampling rate and bandpass also variated across the studies. Three of the studies reported that the EEGLAB toolbox via MATLAB was used to analyse single-trial EEG data. With this information in mind, one can assume that the EEG-recording procedure also varied throughout the studies. Three of the studies also used other physical sensors to capture skin conductance, muscle reactions and heart

| | Hypothesis/ Aims |
|---|---|
| i. | **Aim:** investigate the effects of different interior form features on human brain activity in participants naturally exploring the 3D space (expected significant differences in the perception of different architectural forms in brain regions relevant to shape processing and brain areas related to affective processes). |
| ii. | **Null hypothesis**: the architectural design features used and how they are configured in design don't impact stress levels and hence the human experience in a space.<br>**Alternative hypothesis:** the design features does impact human emotions. |
| iii. | **Objective:** * Analyse the effect that certain characteristics of the design of paediatric waiting rooms have on a companions' stress reduction, addressing the aforementioned limitations. |
| iv. | Explore the mechanism of interaction between environmental information encoded in building space and perceptual feedback provided by the human body. |
| v. | **Hypothesis:** Variations in the virtually presented interiors can activate different cerebral circuits involved in mechanisms of embodiment. |

Table 10 - Hypothesises and aims.

* A hypothesis or aim was not clearly stated in the research article.

| | Neurophysiological findings | Psychological findings |
|---|---|---|
| i. | A strong impact of curvature geometries on activity in the anterior cingulate cortex. Theta band activity in anterior cingulate cortex correlated with specific feature types and geometry. The posterior cingulate cortex and the occipital lobe were involved in the perception of different room perspectives. | Lower **pleasure** and **arousal** ratings in linear geometries, higher in rooms with curvature geometries |
| ii. | More than 40% of the EEG oscillations had higher values across all channels on all frequency band in the **stress-reducing** environment as compared with the **stress-inducing** environment. The findings are only described in percentage. | Subjects felt more **present,** and were more focused and relaxed in the positively configured environment. |
| iii. | EEG-Highbeta* and EEG-AAPEn** data suggests a reduction in stress in all test environments in comparison to the standard waiting room. The environment with relaxing auditory and olfactory features showed the most beneficial effect. The findings only describe changes in the levels of stress (baseline vs. the trial) on scale 0-1. | All environment resulted In **stress** reduction in comparison to the **stress** levels in the standard waiting room. The VE with relaxing visual, features showed the least effect, the VE with relaxing olfactory and auditory showed some effect and the VE with relax-ing auditory and olfactory features had the most effect. |
| iv. | Work **efficiency** was most related to the ß-rhythms seen in several test points and in the right temporal lobe region of the brain. ß-rhythms were closely related to **satisfaction** with human spatial perception. | Participant's **satisfaction** level of spatial perception is directly linked to work efficiency (**attention**). |
| v. | An activation of the frontal-midline theta was seen when subjects felt more **present, familiar** and **comfortable** in the VEs. **Pleasant** VEs increased the theta power across visuomotor circuits and activated the alpha band in areas devoted to visuospatial exploration and processing of categorical spatial relations. | **Pleasantness** was positively correlated with both **novelty** and **arousal**. Novelty was negatively correlated with **familiarity**. |

Table 11 - Neurotheological and psychological findings.

(i) Banaei et al., 2017, (ii) Ergan et al., 2019, (iii) Higuera-Trujillo et al., 2020, (iv) Li et al., 2020, (v) Vecchiato et al., 2015.

* High beta activity (high beta band: 21–30 Hz)
** Amplitude-aware permutation entropy (AAPEn). Permutation entropy (PE) is a method used to evaluate the irregularity of signals. AAPE is a amplitude-aware PE that considers the average of amplitude values and equal amplitude values (Azami and Escudero, 2016).

activity. In these cases, the combined results of the sensor data analysis were used to draw conclusions.

### 3.4.2. Psychological data

Subjective assessment was also an inclusion criterion in the selected studies (see 2. Method). The five studies used different subjective assessment methods with different scoring scales to measure several emotions, including pleasure, arousal, stress, anxiety, attention, comfort, satisfaction, familiarity, novelty, pleasantness, and presence. The self-reported data was produced using Self-Assessment Manikin (SAM), Self-report survey, Stress-self assessment, State Anxiety Inventory, Slater-Usoh-Steed (SUS), and other point scales (see Table 9, p. 74). Psychological data was collected at the end of each trial in four of the studies, whilst one study asked the participants to fill out a self-report survey at the end of the experiment. Several cognitive experiments and a Stroop test were also used to measure the participants' attention during the experiments.

### 3.4.3. Summary of outcome

All studies in this review involved experiments that took place in interior environments with a variety of visual, auditory and, olfactory stimuli. The size of the virtual environment did, however, significantly vary across the studies. A range of different methods, equipment and techniques was used to collect neurophysiological and subjective data to investigate various aims and hypothesis (see Table 10, 76). The numerous variables mentioned above make it impossible to compare most of the results in the studies.

Generally, the researchers found that visual, auditory, and olfactory stimuli had a positive neurophysiological and psychological impact. However, Study (iii) did report a neurophysiological metric (HRV-LFHF) that did not correlate with the two psychological metrics. The authors concluded that similar outcomes have been identified in other studies and that HRV-LFHF is, therefore, an insufficient method to measure the sympathovagal balance. Study (iii) observed a more significant stress reduction using auditory and olfactory stimuli than by visual stimulation. This finding was unique, as none of the other studies used olfactory stimuli. Study (ii and vi) found a correlation between architectural variables with high satisfactory ratings (stress-reducing) and attention and work efficiency. Study (i and v) reported a positive correlation between pleasure and arousal and curvature geometries. A correlation between the neurophysiological findings and the psychological findings was detected in all the studies.

| No. | Question | i. | ii. | iii. | iv. | v. |
|---|---|---|---|---|---|---|
| 1 | Was the purpose stated clearly? | 1 | 1 | 1 | 1 | 1 |
| 2 | Was relevant background literature reviewed? | 1 | 1 | 1 | 1 | 1 |
| 3 | Was the sample described in detail? | 0 | 0 | 0 | 0 | 0 |
| 4 | Was sample size justified? | 0 | 0 | 0 | 0 | 0 |
| 5 | Were the outcome measures reliable? | 0 | 0 | 0 | 0 | 0 |
| 6 | Were the outcome measures valid? | 1 | 1 | 1 | 1 | 1 |
| 7 | Intervention was described in detail? | 1 | 1 | 1 | 1 | 1 |
| 8 | Contamination was avoided? | 1 | 1 | 1 | 1 | 1 |
| 9 | Co-intervention was avoided? | 0 | 1 | 1 | 1 | 1 |
| 10 | Results were reported in terms of statistical significance? | 1 | 1 | 1 | 1 | 1 |
| 11 | Were the analysis method(s) appropriate? | 1 | 1 | 1 | 1 | 1 |
| 12 | Clinical importance was reported? | 1 | 1 | 1 | 1 | 1 |
| 13 | Drop-outs were reported? | 1 | 1 | 1 | 0 | 1 |
| 14 | Conclusions were appropriate given study methods and results | 1 | 1 | 1 | 1 | 1 |
| | Total | 10 | 11 | 11 | 10 | 11 |

Table 12 - Methodological quality assessment of quantitative studies.

(i) Banaei et al., 2017, (ii) Ergan et al., 2019, (iii) Higuera-Trujillo et al., 2020, (iv) Li et al., 2020, (v) Vecchiato et al., 2015.

1 = yes, 0 = no, N/A or not addressed.

## 4. Risk of bias

The validity of my review may have been affected by the research design, procedure, analysis, and reporting. Additionally, the quality and validity of the five included studies also reflect the results and conclusions in this thesis. The Cochrane tool lists five issues that should be considered when assessing the risk of bias (Higgins et al., 2019, Bower et al., 2019).

Allocation
None of the studies revealed how intervention allocation was determined.

Blinding
The purpose of the experiments in all the studies was to some degree exposed to the participants. The conclusion is based on the fact that the participants could see the spaces and rate them during the experiments. The conditions in the physical and virtual environments were controlled during the experiments to avoid unwanted stimuli. The order of the stimuli (trials) was reported to be randomized in Study (i, ii and v), whilst Study (iii and iv) used the same order during all the experiments. It was not reported if the researchers knew the order of which the environments were shown in, but there are reasons to believe that they did due to the procedures that were being used during the experiments.

Incomplete outcome data
Study (i) informed that one of the emotions (dominance) recorded was eliminated after the subjective assessment (SAM-test). This decision was based on missing data differences in the dominance rating in the various environments. Study (ii and iii) also reported that participants were eliminated from the study due to incomplete data recordings.

Selective reporting
All studies reported both significant and non-significant results. Study (ii) only reported the percentage change in the EEG measurements. The researchers argued that sensor measurements might be different in VEs compared to physical spaces and consequently reported the percentage changes and not the absolute values measured in each sensor.

Other potential sources of bias
Only two studies reported that the experiments took place in controlled laboratory environments: Study (iv) reported that laboratory environment control technology (LEC) was used during the experiments to monitor the temperature, humidity, carbon dioxide and formaldehyde concentrations in the laboratory (Li et al., 2020). In Study (iii) the experiments took place

in a controlled laboratory environment. The studies that didn't monitor possible confounding factors may have overestimated the impact of the introduced stimuli.

All studies investigate and try to prove common beliefs, and consequently, the researchers may be biased towards a predetermined outcome.

## 5. Quality assessment

In this review I have rated the studies using the 'Critical Review Form for Quantitative Studies' (Law et al., 1998a). Ideally, there should have been more than one 'rater' to perform the quality assessment and thereby determine the interrater reliability (McHugh, 2012). The 'Guidelines for critical review form-Quantitative studies 1998', was used to ensure that the 'Critical Review Form for Quantitative Studies' was filled out correctly (Law et al., 1998b). Each criterion was rated 1 or 0. Rating 1 means that the criterion was met (YES). Rating 0 means that it was either unclear if the criterion was met or it was not (NO, N/A, Not addressed). Quality assessments are usually done by two or more people, because of limited resources there was just one abstractor and no verifier.

## 6. Discussion

This systematic review investigated current research that has been done in the field of neuroarchitecture. To my knowledge this systematic review is among the first in neuroarchitecture to only include studies in which interior spaces are used as test environments and where both neurophysiological and psychological data were collected. Analytical work was performed to identify the correlation between study outcome and variables such as virtual reality vs. reality, vision vs. multiple senses, and participant characteristics. Further, bias and risks were identified to evaluate the validity of the studies.

The greatest limitation of this review is that there is a very restricted number of studies that have been published in neuroarchitecture. The studies that were found in the search process lacked homogeneity in form of research methods, test environment, sample size, technology, analysis, and outcome. The five studies that matched the inclusion criteria provide a limited amount of information. Hence, conclusions that are made based on the assessment of these studies might be inconclusive.

A quality assessment is usually done by two or more people, but because of limited resources it was only done by one abstractor (me). This might have affected the quality of the selection process, analysis, and outcome of this systematic review. A paradox Is that this shortcoming also represents a major possibility. The lack of comprehensive and well-designed studies in neuroarchitecture makes it an excellent field for future research.

The thorough examination of the five studies resulted in the identification of four topics of interest: (1) The test settings cognitive-emotional impact, (2) A spatial experience is more than just visual, (3) The reality of the virtual space and (4) Objective data collected from subjective participants.

## 6.1 The test settings cognitive-emotional impact

The studies included various visual, auditory, and olfactory stimuli (see Table 6, p.72) added to specific spatial environments (a paediatric waiting room, a bedroom, an educational facility, etcetera). The researchers aimed to investigate how different architectural and design variables affect human emotions, but the emotional impact of the spatial environments themselves was not considered. Therefore, general conclusions should not be drawn based on the results of these studies, as the test environment might influence the collected data. A participant's stress level in a paediatric waiting room test setting may be affected by the participants' past experiences or emotional associations with similar spaces. The personal experience cause changes in the neurophysiological and psychological results unrelated to the added stimuli. Future studies should therefore involve recordings of participants cognitive-emotional response to the same design or architectural variables, but in a series of different settings to achieve more substantial and comparable results.
A proposed future study would be to record neurophysiological and psychological data in different spatial environments, where only one variable (design or architectural feature) changes. This approach would provide information about the emotional effect of the spatial environments and the chosen variable (see Figure 8, p. 81). A series of studies using the proposed methodology could give a fundamental and general understanding of the cognitive-emotional impact of specific design variables and spatial environments.
It is, however, worth mentioning that this proposed study method also

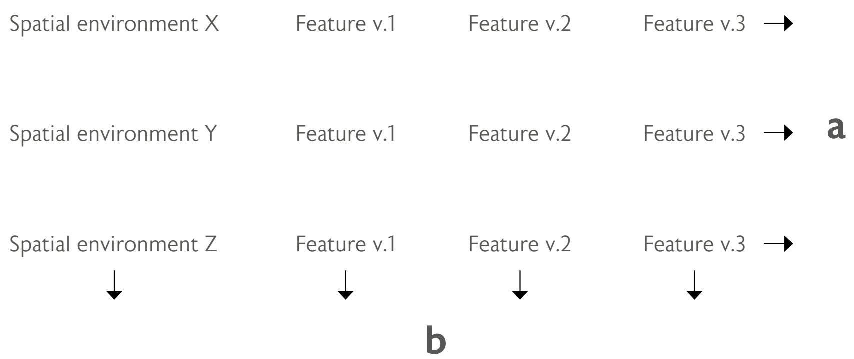



Figure 8 –The architectural test setting: an illustration of a proposed study methodology.

a: The neurophysiological and psychological effect of a feature in different spatial environments.
b: The neurophysiological and psychological effect of different versions of a feature in the same spatial environment.

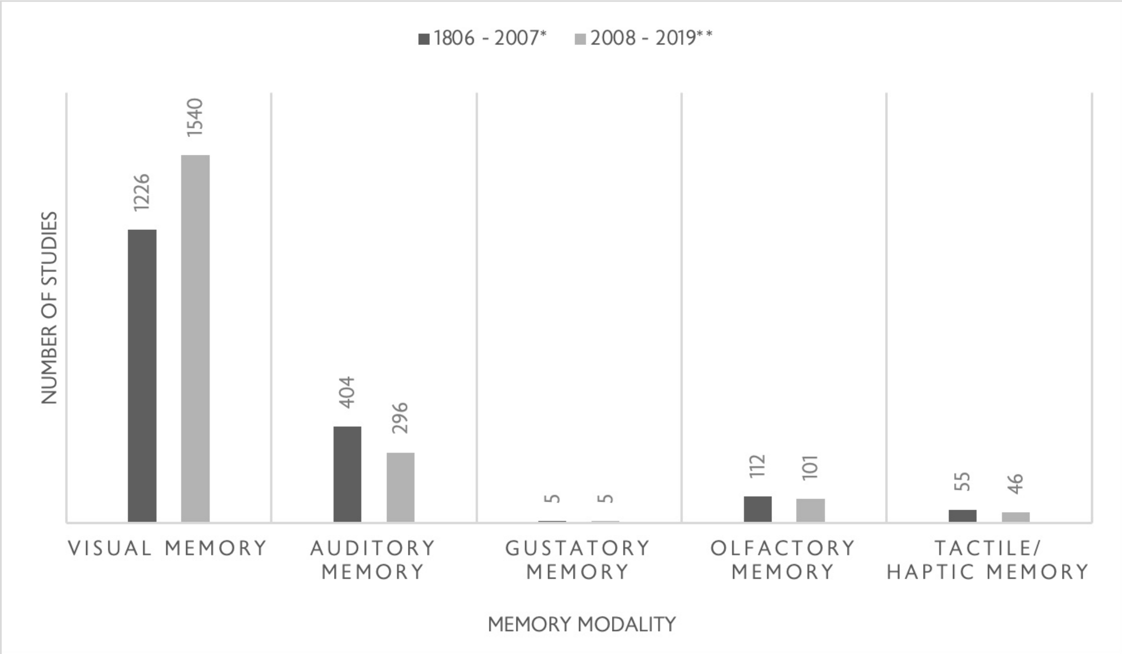



Figure 9 - The number of studies on the different sensory modalities that has been published since 1806.

The data is based on searches in the PsycINFO database and includes studies containing "visual," "auditory," "gustatory," "olfactory" or "tactile/haptic memory".

*The numbers used in the diagram are based on data that was collected in 2007 (Gallace and Spence, 2009).
**The numbers used in the diagram are based on data that was collected in 2019 (Hutmacher, 2019)

involves specific challenges and weaknesses that need to be addressed. Adequate sample size including demographically diverse participants is necessary to ensure so that significant interindividual variations can be identified in the collected data. Analysis and categorisations of numerous studies involving large amounts of experiments would also be necessary to draw informed conclusions. It is also essential that the same physical movements or tasks are performed in all the spaces to avoid movement artefacts that could affect the outcome (Reis et al., 2014). Different spatial environments have different architectural and design features that could affect the results. Therefore, reliable results would only be achieved by performing extensive research and analysis involving all the aforementioned requirements.

## 6.2. A spatial experience is more than just visual

Humans are believed to be visually dominant, and studies have found that vision is both the most important and complex among the senses (Hutmacher, 2019). Two studies that are exploring sensory memory show that there have been published considerably more studies on visual memory than on all other sensory memory (auditory, gustatory, olfactory and tactile/haptic memory) combined in the last 200 years (Gallace and Spence, 2009, Hutmacher, 2019).

Most studies in neuroscience and architecture and neuroscience and aesthetics focus on the cognitive-emotional response to visual stimuli (eye/sight).
Neuroaesthetics is, much like neuroarchitecture, a relatively new field and involves studies on the biological mechanisms and psychological processes evoked by aesthetic experiences (Pearce et al., 2016). Neuroaesthetics focuses on the appraisal of objects (Brown et al., 2011), while neuroarchitecture involves human response to the built environment (Coburn et al., 2017). Neuroarchitecture is, in some cases, based on findings in neuroaesthetics, which can result in misleading conclusions. Misconceptions might be due to the common misbelieve that architectural design only involves aesthetic beauty and is visually experienced (Eberhard, 2009). Furthermore, the historically 'visually-biased nature' (Ebrahem, 2018) of architects might also contribute to the overrepresentation of studies involving visual stimuli in neuroarchitecture.

There has recently emerged a growing interest regarding the mind's response to multisensory stimuli (Cross and Ticini, 2012, Spence, 2020). The temporoparietal junction (TPJ) is a cortical region of the brain that functions chiefly to evoke attention and social cognition, like managing high-level processes involving salient stimuli and reasoning about oneself and others (Bukowski and Lamm, 2017). Scientific findings show that the TPJ is a multisensory integration area (Ionta et al., 2011) that is essential in self-location, also described as the ability to place and experience oneself in a physical space (Aglioti and Candidi, 2011). Multisensory integration is how the combined stimuli from different sensory systems affect processes in the nervous system (Stein et al., 2009). Multisensory stimuli should therefore be considered as necessary when doing experiments involving spatial environments.

Study (iii) found a more significant stress reduction through auditory and olfactory stimuli than visual stimuli. This conclusion, especially if proven appliable in a more general context, could be of great importance in further studies as it proves the neuroscientific importance of other senses than vision.

It is, however, challenging to create controlled test environments that involve multisensory stimuli. Virtual stimuli, such as a building, are constant, while smell and sound are harder to control. VR does make it possible to create multisensory environments in controlled laboratory environments. The fact is that the real world is unpredictable and therefore also uncontrollable. By removing variables in studies to create control, scientists might unintentionally also remove the sense of reality.

## 6.3. The reality of the virtual space

VR is often used in neurophysiological experiments as the participants do not have to physically move to change the environment around them. The participants can perform tasks that generally require physical movement by just pushing buttons or turning their heads. This is helpful during EEG recordings as physical movement can cause artefacts and contaminate results (Islam et al., 2016). Moving by pushing buttons does, however, also cause some limitations regarding proprioception. When walking or performing a task, the brain receives feedback from the body about its perception of its position in space (Grijseels, 2020).

Studies also show that the success rate when performing a task is higher in a virtual environment, which is substantially different from a physical environment, demonstrated in a study. Golfers EEG recordings showed significant changes in cortical brain activation when they played in a physical environment compared to when they played in a virtual environment. Further, the study showed that the success rate was much higher in the virtual environment (Baumeister et al., 2010). The findings suggest that changes in sensory stimulation can affect the activation of the brain's cortical regions, and thereby the outcome.

Both virtual and physical environments can have a stress-reducing effect in humans. However, the physical environment seems to have a more noticeable stress-reducing effect and enhances and promotes restoration (Kjellgren and Buhrkall, 2010). Therefore, the reliability of experimental settings using virtual environments should be carefully considered before implemented in future research.

## 6.4 Objective data collected from subjective participants

All included studies in this review used a before-after design for the experiments, hence the evaluator collected data from each participant before and after treatment (in this case stimuli). This study design is suitable for studies where the researchers do not wish to withhold treatment from any participant. However, the before-after design has certain limitations. A control group is necessary in order to evaluate if the treatment is responsible for the changes in the outcome and not caused by subjective or environmental factors (Law et al., 1998b).

Neuroarchitecture aims to better understand human neurophysiological and psychological responses to the built environment. EEG has become one of the most popular methods to record changes in brain activity both in neuroarchitecture and in other related fields. The technology is inexpensive and assessable, and the procedure is unintrusive. Electrical activity (Hz) is recorded via electrodes attached to the scalp. However, recording a person's emotional state has proven to be a complex task (Mauss and Robinson, 2009).

Like the Savanna Hypothesis, some theories argue that there are universal similarities regarding human aesthetic preferences (Joye, 2007). The brain's ability to read and understand a place has been essential for human survival and existence through history. Much of what we as humans take for granted today, such as modern surroundings, urban environments, and digitalisation, has only existed for a short moment in time. Sjövall explains that if human existence has lasted one day, humans have spent twenty-three hours and fifty-nine seconds on the African Savanna and only a fraction of the last minute in modern surroundings. Human spatial preferences are linked to the ancient parts of the brain and are still influenced by the will to survive on the Savanna either as a hunter or gatherer (Sjövall, 2020). However, the human brain is also plastic and can to some degree change its function to meet new challenges. The modern parts of the brain have evolved and significantly grown both in size and complexity since the time spent on the Savanna and has even been described as "the most complex thing in the universe" (Pacitti et al., 2019).

EEG might be an objective method used to gather data, but demographic characteristics and past experiences make emotions subjective. Therefore, selection criteria are extremely important and gender, cultural, social and personality variables should be carefully considered and balanced when conducting scientific experiments.

Studies have found that subjective characteristics such as personality traits, social and cultural background, and the individuals mental and physical state influence participants ability to engage with scientific experiments (Li et al., 2020). Nadal and Chatterjee argue that the human brain is not programmed to respond to art in a given way, but it is part of human nature to be drawn to familiar and relatable things. Art is a result of the accumulation of a person's subjective, previous experiences (2019). This belief of familiarity and relatability can easily transfer to architecture, and thereby also neuroarchitecture. Studies that aim to produce results with general insights should include participants whose preferences represent the whole population. The determining of adequate sample size and appropriate selection criteria becomes crucial.

EEG studies generally include information about participants gender identity, age, and general health. However, the reporting and specification of inclusion criteria varies, and this review demonstrates that such information is generally lacking in neuroarchitecture articles.
Words like 'normal' and 'healthy' are often used to describe the participant's health. If the author does not mention what definition they have used for these terms, there is a risk for subjective interpretations by the readers. Other helpful information about the participant's demographic characteristics may include medications, race, ethnicity, education level, income, handedness, marital status, IQ, and location. Specific questions and test scores can be used to determine the participant's suitability, and the source of the reported information (e.g., self-reports, questionnaires or physical or mental tests) is also important. EEG studies generally include information about participants gender identity, age, and general health. The reporting and specification of inclusion criteria, however, vary in different research articles:

"healthy volunteers were involved in the study" (Vecchiato et al., 2015)

"based on self-reports, none of them had a history of psychiatric or neurological disorders" (Eqlimi et al., 2020)

"all potential participants self-excluded if there was a history of epilepsy, brain injury or loss of consciousness, history of psychiatric or neurological conditions, or on medication" (Ciorciari et al., 2019)

Gender-specific differences in brain activity have also been seen in participants performing neuropsychological tasks (Ciorciari, 2012). One study found a correlation between general and emotional intelligence and gender (Jausovec and Jausovec, 2005). Resting EEG data from the participants showed that male brain activity decreased simultaneously with general intelligence levels, while female brain activity increased. These findings were most distinctive in the --band oscillations (this involves attention, and controlled access to stored information, Klimesch, 2012). Other studies showed that the menstrual cycle and sex hormones

could affect brain activity (Bazanova et al., 2014, Weis et al., 2019). Such findings, as mentioned above, underline the Importance of taking gender into consideration in neuroscientific studies. A well-designed study therefore needs to be gender balanced.
Conducting experiments and analysing and understanding complex data require training and skills, and not the least a multidisciplinary research team. Emotions are subjective and complex, even when using an easy and objective method to collect EEG data. The variation in sample size and inclusion criteria affect the research's trustworthiness. The current review has demonstrated that a methodological framework and guidelines for research in neuroarchitecture are missing, this needs to be addressed when future studies are designed.

## 6.4. The value of probability

Conducting comprehensive studies can be both time-consuming, costly and require much hard work. Considerable amounts of recourses are invested into research projects, and it is understandable that investigators, therefore, hope for significant findings (Larson and Carbine, 2017). However, data can be manipulated, "if you torture your data long enough, they will tell you whatever you want to hear" (Mills, 1993, p. 1196). Honest exploratory studies should document the number of comparisons, as multiple comparisons can result in false statistically significant findings. In all statistical tests, there is a chance of a false positive (type I error) result (Mills, 1993). The statistically significant threshold usually is 0.05, but when running multiple tests, the type I error increases (Sainani, 2009).
P-values illustrate how likely a finding occurs due to chance (Mills, 1993). Skovlund, argues that a p-value cannot be calculated without a specified research question. Post hoc data analysis and significance tests pursued due to unexpected observations should be clearly stated in the study, as the p-value is less reliable (Skovlund, 2013).

There is a noticeable number of p-values in all the reviewed studies. None of the studies has, however, identified this as a limitation. Overall, the studies identification of limitations mainly involve the test environment and the results. Noticeable, there is a lack of discussion regarding the analysis of these results.

## 7. Conclusion

The field of neuroarchitecture is relatively new, and there is still a significant amount of work left to be done. Many questions have still not been answered and as technology advances It opens up for more accurate research. EEG, like all other available monitor systems, have both advantages and limitations. In order to increase the reliability of data recording, several monitor systems should be used simultaneously during experiments to collect both brain activity and physical responses. Emotions are subjective and complex and conducting trustworthy studies require both objective techniques, subjective assessment, and a multidisciplinary approach.

There is a lack of homogeneity in published research articles in neuroarchitecture. This is a significant limitation and is highlighted in this systematic review. Only five studies met the inclusion criteria.
The lack of a methodological framework and guidelines for how the studies are performed, questions the overall trustworthiness of the research. It seems like there is a missing link in the research that has been conducted so far. The fundamental principles are still to be discovered, and comprehensive research designs are needed to achieve reliable results.

The reviewed studies are of value, even if there are considerable limitations that needs to be addressed. They have laid in place an essential groundwork for further studies to build on. The prospect of neuroarchitecture is bright, judging by the number of studies that are currently being published in the field. It is nevertheless hard to predict how neuroarchitecture will evolve and to what extent new research findings will impact the built environment.

## Tables

# Figures

# References


BANAEI, M., AHMADI, A. & YAZDANFAR, A. 2017a. Application of AI methods in the clustering of architecture interior forms. Frontiers of Architectural Research, 6, 360-373.

BANAEI, M., HATAMI, J., YAZDANFAR, A. & GRAMANN, K. 2017b. Walking through Architectural Spaces: The Impact of Interior Forms on Human Brain Dynamics. Frontiers in Human Neuroscience, 11.

BORGIANNI, Y. & MACCIONI, L. 2020. Review of the use of neurophysiological and biometric measures in experimental design research. AI EDAM, 34, 248-285.

BOWER, I., TUCKER, R. & ENTICOTT, P. G. 2019. Impact of built environment design on emotion measured via neurophysiological correlates and subjective indicators: A systematic review. Journal of environmental psychology, 66, 101344.

BUTTON, K. S., IOANNIDIS, J. P. A., MOKRYSZ, C., NOSEK, B. A., FLINT, J., ROBINSON, E. S. J. & MUNAFÒ, M. R. 2013. Power failure: why small sample size undermines the reliability of neuroscience. Nature Reviews Neuroscience, 14, 365-376.

COLLABORATION, O. S. 2015. Estimating the reproducibility of psychological science. Science, 349.

DE KROON, J. P. & BRAS, B. 2003. Practical Considerations for Setting Up A Virtual Reality System for Virtual Prototyping. Journal of Computing and Information Science in Engineering, 3, 266-271.

ERGAN, S., RADWAN, A., ZOU, Z. B., TSENG, H. A. & HAN, X. 2019. Quantifying Human Experience in Architectural Spaces with Integrated Virtual Reality and Body Sensor Networks. Journal of Computing in Civil Engineering, 33.

GUSENBAUER, M. & HADDAWAY, N. R. 2020. Which academic search systems are suitable for systematic reviews or meta-analyses? Evaluating retrieval qualities of Google Scholar, PubMed, and 26 other resources. Research synthesis methods, 11, 181-217.

HIGGINS, J. P., SAVOVI- , J., PAGE, M. J., ELBERS, R. G. & STERNE, J. A. 2019. Assessing risk of bias in a randomized trial. Cochrane Handbook for Systematic Reviews of Interventions. 2nd ed. Chichester, UK: John Wiley & Sons, 2019.

HIGUERA-TRUJILLO, J. L., MILLAN, C. L., AVI?O, A. M. I. & ROJAS, J. C. 2020. Multisensory stress reduction: A neuro-architecture study of paediatric waiting rooms. Journal of Planning Literature, 35, 365-365.

IMOTIONS 2019. Electroencephalography - The Complete Pocket Guide. iMotions.

KOIKE, S., NISHIMURA, Y., TAKIZAWA, R., YAHATA, N. & KASAI, K. 2013. Near-Infrared Spectroscopy in Schizophrenia: A Possible Biomarker for Predicting Clinical Outcome and Treatment Response. Frontiers in Psychiatry, 4.

LAKHANI, A., NORWOOD, M., WATLING, D. P., ZEEMAN, H. & KENDALL, E. 2019. Using the natural environment to address the psychosocial impact of neurological disability: A systematic review. Health & Place, 55, 188-201.

LAKHANI, A., TOWNSEND, C. & BISHARA, J. 2017. Traumatic brain injury amongst indigenous people: a systematic review. Brain injury, 31, 1718-1730.

LARSON, M. J. & CARBINE, K. A. 2017. Sample size calculations in human electrophysiology (EEG and ERP) studies: A systematic review and recommendations for increased rigor. International Journal of Psychophysiology, 111, 33-41.

LAW, M., STEWART, D., POLLOCK, N., LETTS, L., BOSCH, J. & WESTMORLAND, M. 1998a. Critical Review Form–Quantitative Studies McMaster University.

LAW, M., STEWART, D., POLLOCK, N., LETTS, L., BOSCH, J. & WESTMORLAND, M. 1998b. Guidelines for critical review form-Quantitative studies, 1998. MMcMaster University.

LI, J., JIN, Y., LU, S., WU, W. & WANG, P. 2020. Building environment information and human perceptual feedback collected through a combined virtual reality (VR) and electroencephalogram (EEG) method. Energy and Buildings, 224, 110259.

LOUW, A., DIENER, I., BUTLER, D. S. & PUENTEDURA, E. J. 2011. The effect of neuroscience education on pain, disability, anxiety, and stress in chronic musculoskeletal pain. Archives of physical medicine and rehabilitation, 92, 2041-2056.

MCHUGH, M. L. 2012. Interrater reliability: the kappa statistic. Biochemia medica, 22, 276-282.

MCLOUGHLIN, G., MAKEIG, S. & TSUANG, M. T. 2014. In search of biomarkers in psychiatry: EEG- based measures of brain function. American Journal of Medical Genetics Part B: Neuropsychiatric Genetics, 165, 111-121.

MILLS, J. L. 1993. Data Torturing. New England Journal of Medicine, 329, 1196-1199.

MOHER, D., LIBERATI, A., TETZLAFF, J. & ALTMAN, D. G. 2009. Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. BMJ, 339, b2535.

NORWOOD, M. F., LAKHANI, A., MAUJEAN, A., ZEEMAN, H., CREUX, O. & KENDALL, E. 2019. Brain activity, underlying mood and the environment: A systematic review. Journal of Environmental Psychology, 65, 101321.

NTNU 2021. Introduction to EndNote 20. NTNU University Library, Medicine and Health Library.

PAGE, M. J., MOHER, D., BOSSUYT, P. M., BOUTRON, I., HOFFMANN, T. C., MULROW, C. D., SHAMSEER, L., TETZLAFF, J. M., AKL, E. A. & BRENNAN, S. E. 2021. PRISMA 2020 explanation and elaboration: updated guidance and exemplars for reporting systematic reviews. bmj, 372.

RETHLEFSEN, M. L., KIRTLEY, S., WAFFENSCHMIDT, S., AYALA, A. P., MOHER, D., PAGE, M. J. & KOFFEL, J. B. 2021. PRISMA-S: an extension to the PRISMA Statement for Reporting Literature Searches in Systematic Reviews. Systematic reviews, 10, 1-19.

SAINANI, K. L. 2009. The Problem of Multiple Testing. PM&R, 1, 1098-1103.

SKOVLUND, E. 2013. [Ask first, then count]. Tidsskr Nor Laegeforen, 133, 10.

VECCHIATO, G., TIERI, G., JELIC, A., DE MATTEIS, F., MAGLIONE, A. G. & BABILONI, F. 2015. Electroencephalographic Correlates of Sensorimotor Integration and Embodiment during the Appreciation of Virtual Architectural Environments. Front Psychol, 6, 1944.

YOST, J., DOBBINS, M., TRAYNOR, R., DECORBY, K., WORKENTINE, S. & GRECO, L. 2014. Tools to support evidence-informed public health decision making. BMC public health, 14, 1-13.

# 7. Discussion

I must admit, that at first glance, it appears like neuroscience and architecture have little in common. At the start of my thesis, I was concerned that the merging of neuroscience in architecture would limit architect's creativity. Since then, I have realised that this is not the case at all. The purpose of neuroscientific findings is not to dictate how buildings should be designed but rather to support architects during the design process.
Neuroarchitecture mainly explores the interaction between humans and the built environment to improve urban-, architectural- and interior spaces. Recent discoveries demonstrate that features such as lighting, greenery, colours, materials, forms, etcetera impact several emotions, including stress, comfort, pleasantness, and arousal.

Architects have traditionally been making design choices based on their subjective intuition and experiences. Newly developed technology and methodologies in neuroscience can prove the accuracy of theories that have earlier only been based on assumptions. Moreover, identifying environmental stressors that affect humans' mental and physical health will help architects make decisions that positively impact the built environment.

Buildings are designed for the occupants. So, should we not embrace neuroscience if it can give us a better understanding of how design features influence humans mental and physical health?

The risk of subjective influence is a liability in both research articles and systematic reviews. Throughout my thesis I have explained that neuroarchitecture is a multidisciplinary field where architects and neuroscientists collaborate to better understand how built environments affects humans. However, after reading numerous articles it appears to me that most, if not all authors in the studies are architects.

Limited competence and lacking knowledge among researchers can affect a study's credibility as described below:

**Collecting data**
The investigator who is collecting data should both have knowledge about the research field and the specific study to determine the technology and methods that are best suited for the experiment. Training is also necessary to ensure that the equipment is rightfully used, and that the data is usable.

**Analysing data**
The investigator who is analysing the data needs to have a suitable professional background and knowledge about the collected data, and statistical skills to ensure that the conclusions are trustworthy.

**Reading articles**
The readers ability to understand and assess the validity of an article is determined by relevant competence and knowledge.

I had very little previous knowledge in neuroscience or in academic writing when I started this project. I used the first two month of this project to learn about neuroscience, study designs, statistics, and academic writing to understand the research articles. Even so there is obviously still a possibility that I have misinterpreted information in the articles. The systematic review included the articles I think are of relevance. Even if the methods I used were objective, the analysis of the studies are based on my background knowledge and interpretation.

When I was reading studies, it became clear that a hug array of methods, techniques and test settings are currently being used in neuroarchitectural research. This makes it impossible to compare different studies. An additional shortcut is that detailed protocols are usually missing and replicating the studies are therefore not possible. With this background it is hard to assess the quality of the study and how trustworthy the results are. Neuroarchitecture is yet to develop standards, cross-validated protocols, and methods (guidelines) for collecting, processing and analysing data. All this is crucial to increase the quality, reproducibility, and thus the reliability of future research.
Technology is continuously advancing, and the test environments are becoming more realistic with multisensory stimuli and better lab environments. Further research may focus on measuring brain activity (fMRI, EEG), ectodermal activity (EDA), heart rate (HVR, PPG), muscle response (EMG), and eye movement (eyetracking) simultaneously. Data extraction from various sources will give a better understanding of both the body's and brain's responses and paint a more elaborate picture of how architecture affects us.

Findings in neuroscience can lead to new building standards that will improve buildings. This will ensure that the quality of future buildings is based on the need for human's wellbeing and not sacrificed in favour of unreasonable budget cuts or not well thought through choices.

## The differentiation between 'Place' and 'Space'

Novel studies in cognitive neuroscientific research have started to uncover how humans navigate in space as well as humans physiological, cognitive, and emotional responses to the built environment.

Recent discoveries of neural activity within the hippocampus have led to a better understanding of spatial perception, memory and navigation. The new findings stress the importance of creating architectural environments where the functionality (movement and usage of space) and aesthetic elements (physical layout and form) are involved.

A place is defined by physical elements or by factors that impact the Individuals path of movement. The following examples explain how a space can involve several places:
An office area, divided by glass partition walls may be perceived as one space. The hippocampus will however separate the office into different places depending on the limitation in movement caused by the physical elements (glass walls).
A hallway can also be considered as a space. The hippocampus does however perceive it as different places depending on the direction the individual is moving in. Each direction involves separate patterns of neural activity that are determined by the path.

Spaces that encourage free movement provide a stronger sense of place. Such spaces encourage us to stay in a space rather than just passing through (Sternberg and Wilson, 2006).

STERNBERG, E. M. & WILSON, M. A. 2006. Neuroscience and Architecture: Seeking Common Ground. Cell, 127, 239-242.

# Appendix A: Supplementary material

Full search strategy for the systematic review, The emotional impact of built interior environments objectively measured by electrical activity (EEG) and subjective assessments: A systematic review

The data search description was based on the layout of the notes to published systematic reviews (Bennett et al., 2018, Rethlefsen et al., 2021).

# 1. Database Search (initial search)

Notes

- Total number of citations = 890
- Total number of citations after duplicates removed = 346
- Duplicates removed in Endnote 20
- References of included studies were checked
- Most terms were not applied to the query box, but added as filters

Terms

- Title search
- Publication year: 2010-2020
- Text availability: Full text
- Study type: Journal Article
- Language: English
- Publication stage: Final

## 1.1. Journals

**Scopus - Full index (395 on March 29, 2021)**
Advanced document search: (TITLE((Electroencephalography OR EEG OR "event related potential" OR ERP OR "brain oscillations" OR "brain activity" OR "cerebral activity" OR "brain response*" OR "Physiological response" OR "Neurophysiological responses") AND (built OR space OR "physical environment" OR "spatial environment" OR "virtual environment" OR environment* OR "architectural space" OR "architecture*" OR "neuroarchitecture"))

Results by year: 2010: 18, 2011: 21, 2012: 22, 2013: 20, 2014: 35, 2015: 30, 2016:32, 2017: 44, 2018: 46, 2019: 60, 2020: 67.

**MEDLINE - Search system: PubMed (130 on March 29, 2021)**
Advanced document search: (Electroencephalography*[Title] OR EEG*[Title] OR ERP[Title] OR (event related potential[Title]) OR (brain oscillation[Title]) OR (brain activity[Title]) OR (brain response[Title]) OR (cerebral activity[Title]) OR (Physiological response[Title]) OR (Neurophysiological response[Title])) AND (built[Title] OR space[Title] OR (physical environment[Title]) OR (spatial environment[Title]) OR (virtual environment[Title]) OR environment*[Title] OR (architectural space[Title]) OR architecture*[Title] OR neuroarchitecture[Title])

Results by year: 2010: 11, 2011: 12, 2012: 9, 2013: 11, 2014: 14, 2015: 14, 2016:11, 2017: 20, 2018: 22, 2019: 26, 2020: 13.

Web of Science Core Collection - Search system: Web of Science (265 on March 29, 2021)
Advanced document search: (TI=((Electroencephalography* OR EEG* OR ERP OR (event related potential) OR (brain oscillation) OR (brain activity) OR (brain response) OR (cerebral activity) OR (Physiological response) OR (Neurophysiological response) )AND (built OR space OR (physical environment) OR (spatial environment) OR (virtual environment) OR environment* OR (architectural space) OR architecture* OR neuroarchitecture)))

Results by year: 2010: 11, 2011: 10, 2012: 11, 2013: 13, 2014: 18, 2015: 21, 2016: 20, 2017: 31, 2018: 36, 2019: 49, 2020: 45.

**APA PsycInfo - Search system: PsycARTICLES (70 on 30 March 2021)**
Advanced document search: (Title: Electroencephalography* OR Title: EEG* OR Title: ERP OR (Title: event related potential) OR (Title: brain oscillation) OR (Title: brain activity) OR (Title: brain response) OR (Title: cerebral activity) OR (Title: Physiological response) OR (Title: Neurophysiological response)) AND (Title: built OR Any Field: space OR (Title: physical environment) OR (Title: spatial environment) OR (Title: virtual environment) OR Title: environment* OR (Title: architectural space) OR Title: architecture* OR Title: neuroarchitecture)

Results by year: 2010: -, 2011: 5, 2012: 2, 2013: 3, 2014: 5, 2015: 7, 2016: 7, 2017: 6, 2018: 11, 2019: 17, 2020: 7.

**CINAHL - Search system: EBSCOhost (22 on 30 March 2021)**
Advanced document search: TI((Electroencephalography* OR EEG* OR ERP OR (event related potential) OR (brain oscillation) OR (brain activity) OR (brain response) OR (cerebral activity) OR (Physiological response) OR (Neurophysiological response)) AND TI(built OR space OR (physical environment) OR (spatial environment) OR (virtual environment) OR environment* OR (architectural space) OR architecture* OR neuroarchitecture)

Results by year: 2010: 2, 2011: 2, 2012: 2, 2013: 2, 2014: -, 2015: 2, 2016: 2, 2017: 3, 2018: 2, 2019: 4, 2020: 1.

**Psychology and Behavioral Sciences Collection - Search system: EBSCOhost (8 on 30 March 2021)**
Advanced document search: TI((Electroencephalography* OR EEG* OR ERP OR (event related potential) OR (brain oscillation) OR (brain activity) OR (brain response) OR (cerebral activity) OR (Physiological response)

OR (Neurophysiological response)) AND TI(built OR space OR (physical environment) OR (spatial environment) OR (virtual environment) OR environment* OR (architectural space) OR architecture* OR neuroarchitecture)

Results by year: 2010: -, 2011: 1, 2012: 1, 2013: 1, 2014: -, 2015: 1, 2016: -, 2017: -, 2018: 1, 2019: 2, 2020: 1.

## 2. Articles previously known to author

Notes
- Total number of citations = 8
- Previously known to author
- Not present in the database search
- Studies published in journals with high impact and manually

Terms
- Publication year: 2010-2020
- Text availability: Full text
- Study type: Journal Article
- Source: Journal
- Language: English
- Publication stage: Final
- Title must be of relevance (Include search phrases that were used in the initial database title search or be of specific interest)
- A high number of citations were not a considered limitation as the field of Neuroarchitecture is relatively new and narrow

1. Evaluating the impact of viewing location on view perception using a virtual environment (8 April 2021)

2. Walking through Architectural Spaces: The Impact of Interior Forms on Human Brain Dynamics (8 April 2021)

3. Subjective and physiological responses to façade and sunlight pattern geometry in virtual reality (8 April 2021)

4. Quantifying Human Experience in Architectural Spaces with Integrated Virtual Reality and Body Sensor Networks (8 April 2021)

5. Multisensory stress reduction: a neuroarchitecture study of paediatric waiting rooms (8 April 2021)

6. Physiological Arousal Quantifying Perception of Safe and Unsafe Virtual Environments by Older and Younger Adults (8 April 2021)

7. Effects of biophilic interventions in office on stress reaction and cognitive function: A randomized crossover study in virtual reality (8 April 2021)

8. Influence of the Acoustic Environment in Hospital Wards on Patient Physiological and Psychological Indices (8 April 2021)

## 3. Backward citation chasing

Notes
- Total number of citations = 410
- Total number of citations after duplicates removed = 2
- Duplicates removed in Endnote 20
- Terms were applied directly to each of the reference lists
- Selected references were added manually to Endnote 20

Terms
- Publication year: 2010-2020
- Text availability: Full text
- Study type: Journal Article
- Source: Journal
- Language: English
- Publication stage: Final
- Title must be of relevance (Include search phrases that were used in the initial database title search or be of specific interest)
- A high number of citations were not a considered limitation as the field of Neuroarchitecture is relatively new and narrow

**Titles of studied included in the literature review from initial database search**

1. Building environment information and human perceptual feedback collected through a com-bined virtual reality (VR) and electroencephalogram (EEG) method. (57 on 9 April 2021)
2. Using Neurology Sciences to Investigate the Color Component and Its Effect on Promoting the Sense of Spirituality in the Interior Space of the Vakil Mosque of Shiraz. (50 on 9 April 2021)
3. Neural-signal electroencephalogram (EEG) methods to improve human-building interaction under different indoor air quality (37 on 9 April 2021)
4. Adolescents Environmental Emotion Perception by Integrating EEG and Eye Movements (46 on 9 April 2021)

**From studies previously known to author**

5. Walking through Architectural Spaces: The Impact of Interior Forms on Human Brain Dynamics . (72 on 8 April 2021)
6. Quantifying Human Experience in Architectural Spaces with Integrated Virtual Reality and Body Sensor Networks. (63 on 8 April 2021)
7. Multisensory stress reduction: a neuroarchitecture study of paediatric waiting rooms. (84 on 8 April 2021)

## 4. Forward citation chasing

Notes
- Total number of citations = 409
- Total number of citations after duplicates removed = 2
- Duplicates removed in Endnote 20
- Forward citation chasing was conducted by using Google Scholar.
- All citations were added manually to Endnote 20

Terms
- Publication year: 2010-2020
- Text availability: Full text
- Study type: Journal Article
- Source: Journal
- Language: English
- Publication stage: Final
- Title must be of relevance (Include search phrases that were used in the database title search or be of specific interest)
- A high number of citations were not a considered limitation as the field of Neuroarchitecture is relatively new and narrow

**Titles of studied included in the literature review from initial database search**

1. Building environment information and human perceptual feedback collected through a com-bined virtual reality (VR) and electroencephalogram (EEG) method. (3 on 9 April 2021)
2. Using Neurology Sciences to Investigate the Color Component and Its Effect on Promoting the Sense of Spirituality in the Interior Space of the Vakil Mosque of Shiraz. (10 on 9 April 2021)
3. Neural-signal electroencephalogram (EEG) methods to improve human-building interaction under different indoor air quality (4 on 9 April 2021)
4. Adolescents Environmental Emotion Perception by Integrating EEG and Eye Movements (2 on 9 April 2021)

**From studies previously known to author**

5. Walking through Architectural Spaces: The Impact of Interior Forms on Human Brain Dynamics . (57 on 9 April 2021)
6. Quantifying Human Experience in Architectural Spaces with Integrated Virtual Reality and Body Sensor Networks. (33 on 9 April 2021)
7. Multisensory stress reduction: a neuroarchitecture study of paediatric waiting rooms. (9 on 9 April 2021)

## 5. Inclusion criteria

The following search limits were then applied to the initial database search:

- The search was limited to the English language.
- The search was limited published articles that were available in full version.
- The search was limited to articles published articles from 2010 to 2020 as the field of Neuroarchitecture is relatively new and consequently rapidly evolving. Studies published in this time period was therefore considered to best reflect the current situation and findings.
- The search was limited to published journal articles to ensure quality and relevance. Excluded publication types included conference papers, bachelor thesis, master thesis, PHD thesis, book chapters and literature reviews.

## 6. Articles Impact

### Walking through Architectural Spaces: The Impact of Interior Forms on Human Brain Dynamics (information from 19 April 2021)

Total views: 21 817
Total citations: 28
(Frontiers, 2021a)

Journal: Frontiers in Human Neuroscience
Journal impact 2019: 2.673
Categories: Neuroscience, Psychology
(Clarivate, 2021)

### Quantifying Human Experience in Architectural Spaces with Integrated Virtual Reality and Body Sensor Networks (information from 19 April 2021)

Total downloads: 1192 times
(ASCE, 2021)

Journal: Journal of Computing in Civil Engineering
Journal impact 2019: 2.979
Categories: Civil Engineering
Clarivate, 2021)

### Multisensory stress reduction: a neuro-architecture study of paediatric waiting rooms (information from 20 April 2021)

Total views: 578
Total citations: 6
(Informa, 2021)

Journal: Building Research & Information
Journal impact 2019: 3.887
Categories: Construction and building technology
Clarivate, 2021)

**Building environment information and human perceptual feedback collected through a combined virtual reality (VR) and electroencephalogram (EEG) method (information from 20 April 2021)**

Total views: 33
Total citations: 3
(Plum, 2021)

Journal: Energy and Buildings
Journal impact 2019: 4.867
Categories: Construction and building technology
Clarivate, 2021)

**Electroencephalographic Correlates of Sensorimotor Integration and Embodiment during the Appreciation of Virtual Architectural Environments (information from 20 April 2021)**

Total views: 6082
Total citations: 22
(Frontiers, 2021b)

Journal: Frontiers in Psychology
Journal impact 2019: 2.067
Categories: Psychology, Multidisciplinary science
Clarivate, 2021)

# References

D-ALHAMID, F., KENT, M., CALAUTIT, J. & WU, Y. 2020. Evaluating the impact of viewing location on view perception using a virtual environment. Building and Environment, 180, 106932.

ASCE. 2021. American Society of Civil Engineers [Online]. Available: https://ascelibrary.org [Accessed April 19th 2021].

BANAEI, M., HATAMI, J., YAZDANFAR, A. & GRAMANN, K. 2017. Walking through Architectural Spaces: The Impact of Interior Forms on Human Brain Dynamics. Frontiers in Human Neuroscience, 11.

BENNETT, K. G., BERLIN, N. L., MACEACHERN, M. P., BUCHMAN, S. R., PREMINGER, B. A. & VERCLER, C. J. 2018. The ethical and professional use of social media in surgery—a systematic review of the literature. Plastic and reconstructive surgery, 142, 388e.

CHAMILOTHORI, K., CHINAZZO, G., RODRIGUES, J., DAN-GLAUSER, E., WIENOLD, J. & ANDERSEN, M. 2019. Subjective and physiological responses to façade and sunlight pattern geometry in virtual reality. Building and Environment, 150, 144-155.

CLARIVATE. 2021. InCite Journal Citation Reports [Online]. Clarivate. Available: https://jcr.clarivate.com [Accessed April 19th 2021].

ERGAN, S., RADWAN, A., ZOU, Z. B., TSENG, H. A. & HAN, X. 2019. Quantifying Human Experience in Architectural Spaces with Integrated Virtual Reality and Body Sensor Networks. Journal of Computing in Civil Engineering, 33.

FRONTIERS. 2021a. Frontiers in Human Neuroscience [Online]. Available: https://www.frontiersin.org [Accessed April 19th 2021].

FRONTIERS. 2021b. Frontiers in Psychology [Online]. Available: https://www.frontiersin.org [Accessed April 19th 2021].

HABIBABAD, A. S., MANDINEJAD, J. E. D., AZEMATI, H. & MATRACCHI, P. 2019. Using Neurology Sciences to Investigate the Color Component and Its Effect on Promoting the Sense of Spirituality in the Interior Space of the Vakil Mosque of Shiraz (Using Quantitative Electroencephalography Wave Recording). Journal of Religion & Health.

HIGUERA-TRUJILLO, J. L., MILLAN, C. L., AVI?O, A. M. I. & ROJAS, J. C. 2020. Multisensory stress reduction: A neuro-architecture study of paediatric waiting rooms. Journal of Planning Literature, 35, 365-365.

INFORMA. 2021. Taylor & Francis Group [Online]. Available: https://www.tandfonline.com [Accessed April 19th 2021].

LEITE, S., DIAS, M. S., ELOY, S., FREITAS, J., MARQUES, S., PEDRO, T. & OURIQUE, L. 2019. Physiological arousal quantifying perception of safe and unsafe virtual environments by older and younger adults. Sensors, 19, 2447.

LI, J., JIN, Y., LU, S., WU, W. & WANG, P. 2020. Building environment information and human perceptual feedback collected through a combined virtual reality (VR) and electroencephalogram (EEG) method. Energy and Buildings, 224, 110259.

PLUM. 2021. Elsevier [Online]. Plum Analytics. Available: https://plu.mx [Accessed April 19th 2021].

RETHLEFSEN, M. L., KIRTLEY, S., WAFFENSCHMIDT, S., AYALA, A. P., MOHER, D., PAGE, M. J. & KOFFEL, J. B. 2021. PRISMA-S: an extension to the PRISMA Statement for Reporting Literature Searches in Systematic Reviews. Systematic reviews, 10, 1-19.

SHAN, X., YANG, E. H., ZHOU, J. & CHANG, V. W. C. 2019. Neural-signal electroencephalogram (EEG) methods to improve human-building interaction under different indoor air quality. Energy and Buildings, 197, 188-195.

SU, Y. Y., LI, W. C., BI, N. & LV, Z. 2019. Adolescents Environmental Emotion Perception by Integrating EEG and Eye Movements. Frontiers in Neurorobotics, 13.

YIN, J., ARFAEI, N., MACNAUGHTON, P., CATALANO, P. J., ALLEN, J. G. & SPENGLER, J. D. 2019. Effects of biophilic interventions in office on stress reaction and cognitive function: A randomized crossover study in virtual reality. Indoor air, 29, 1028-1039.

ZHOU, T., WU, Y., MENG, Q. & KANG, J. 2020. Influence of the acoustic environment in hospital wards on patient physiological and psychological indices. Frontiers in Psychology, 11.

# Appendix B: Screening and study selection

Mean number of participants across the 5 selected studies

$$\mu = \frac{\mathbf{15}\text{ (Banaei et al., 2017)} + \mathbf{32}\text{ (Ergan et al., 2019)} + \mathbf{24}\text{ (Higuera-Trujillo et al., 2020)} + \mathbf{30}\text{ (Li et al., 2020)} + \mathbf{17}\text{ (Vecchiato et al., 2015)}}{\mathbf{5}} = \mathbf{23.6}$$

Standard deviation across the 5 selected studies

$$SD_{sample} = \sqrt{\frac{\sum |x - \mu|^2}{N}}$$

Count, N: 5
Sum, $\Sigma x$: 118
Mean, $\mu$: 23.6
Variance, $\sigma^2$: 45.84

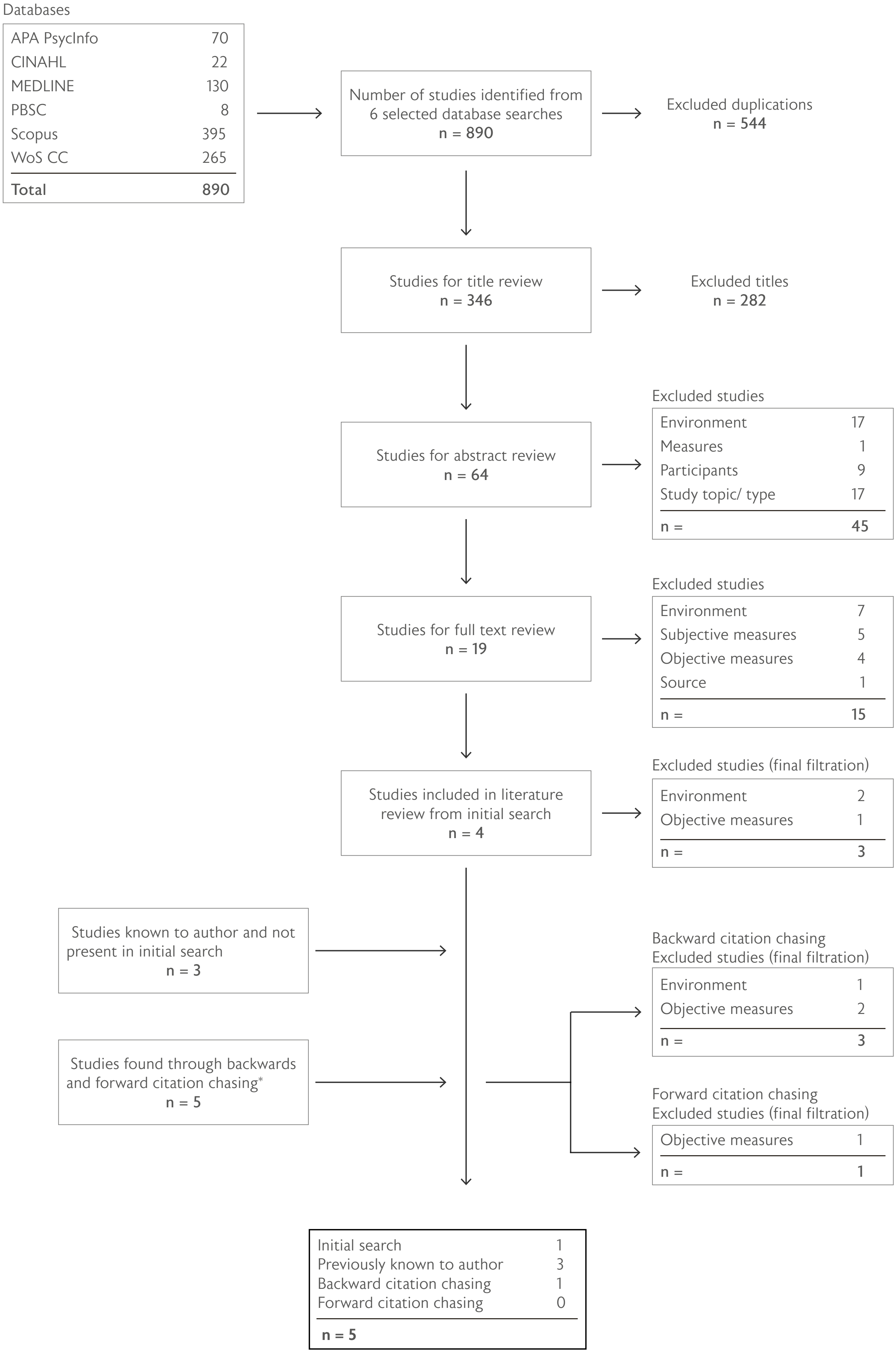
$|x - \mu|^2$

$|15 - 23.6|^2 = 73.96$
$|32 - 23.6|^2 = 70.56$
$|24 - 23.6|^2 = 0.16$
$|30 - 23.6|^2 = 40.96$
$|17 - 23.6|^2 = 43.56$

$\sum |x - \mu|^2 = 229.2$

$$\frac{\sum |x - \mu|^2}{N} = \frac{229.2}{5} = 45.84$$

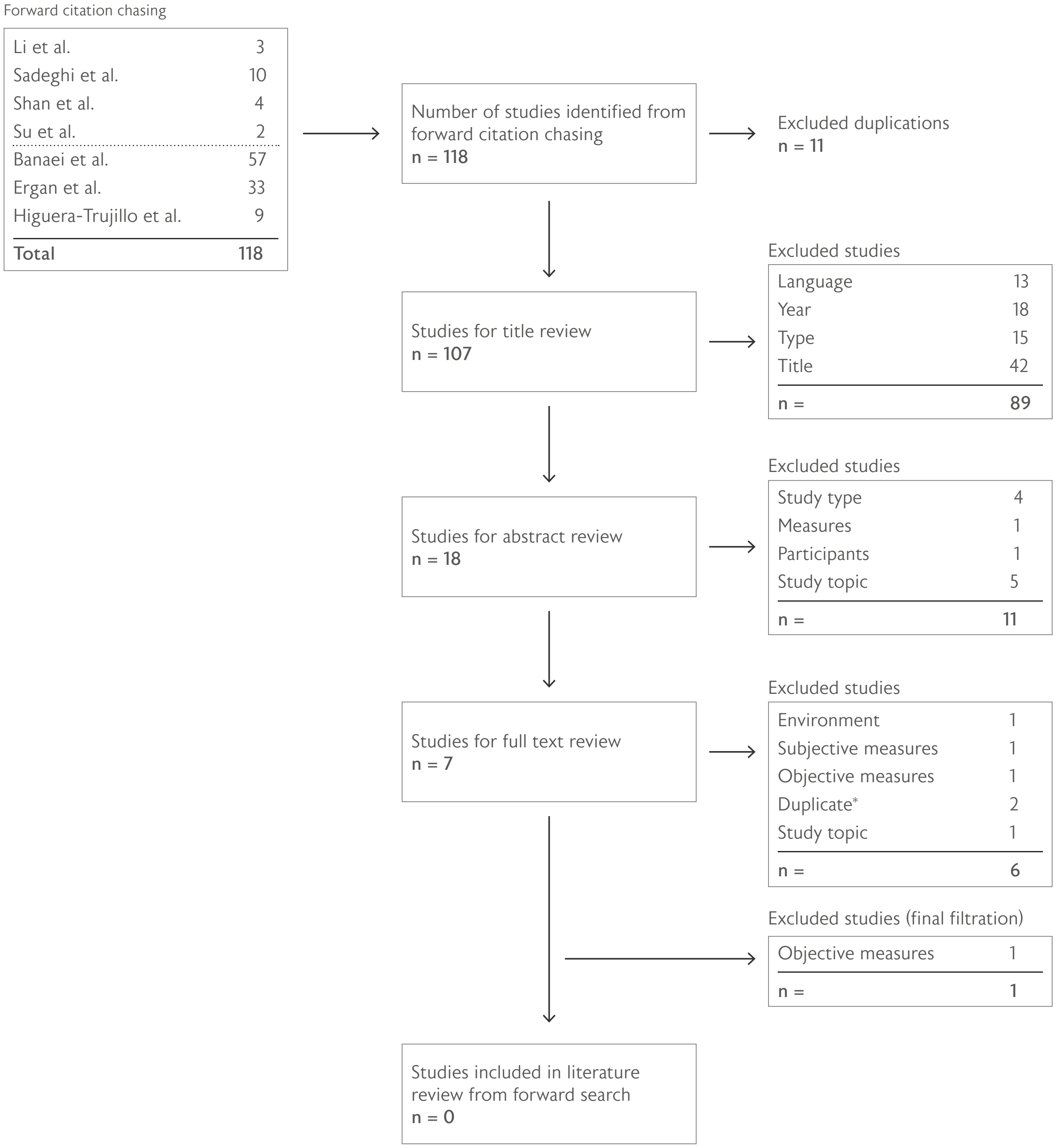
$$\sqrt{\frac{\sum |x - \mu|^2}{N}} = \sqrt{45.84} \approx \mathbf{6.77}$$




Citation chasing was conducted for systematic review, *The emotional impact of built interior environments objectively measured by electrical activity (EEG) and subjective assessments: A systematic review* by reviewing the citations (backwards citation chasing) and by using Google Scholar (forward citation chasing)

Article information (initial search)

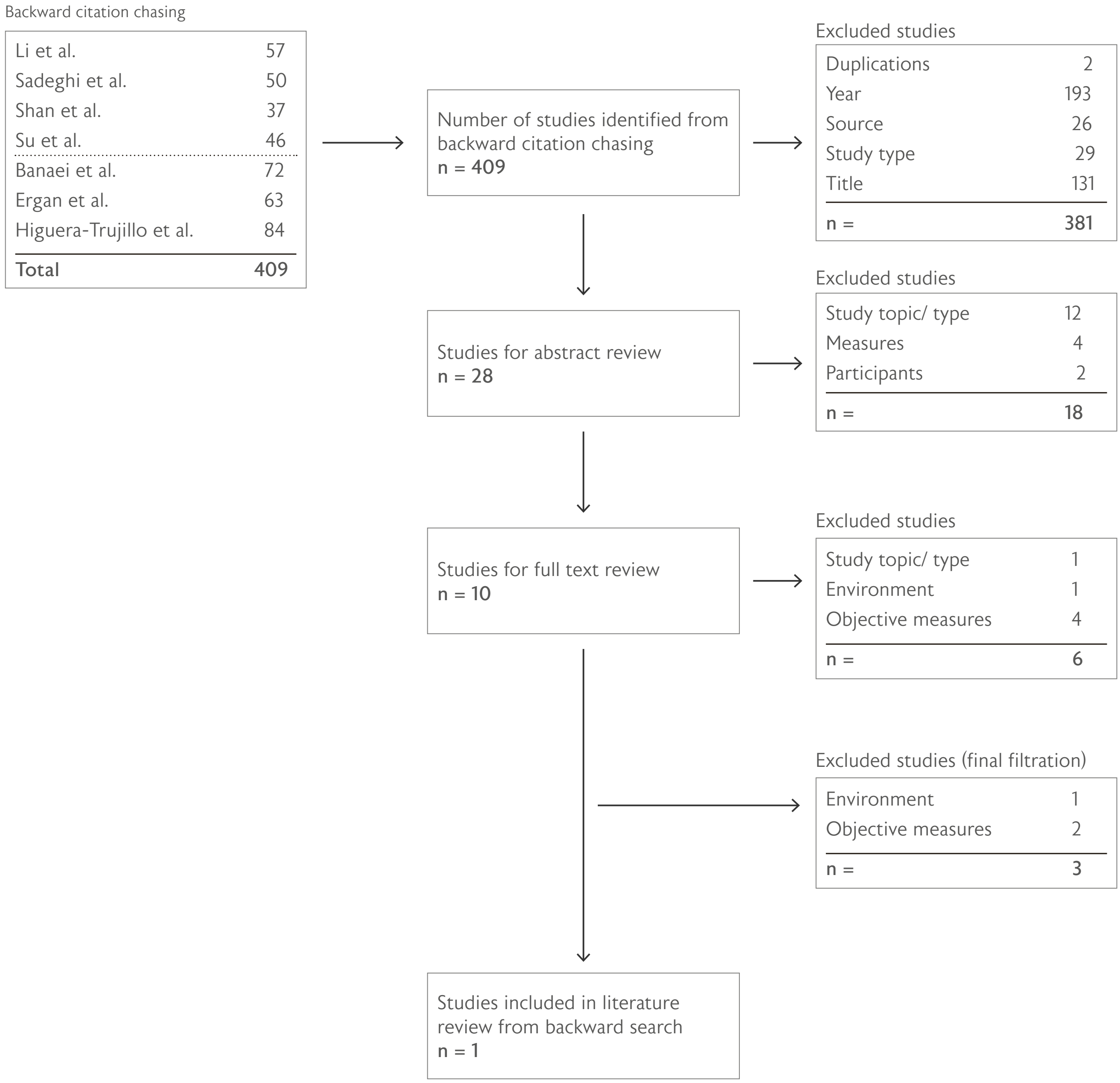
| Author | Title | Year | Cited* | Part.** | Environment | | | Stimuli | | | | | | | | Obj. messures | | | | | | | | | Sub. messures | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Laboratory | Naturalistic | Natural | Images | Video | Virtual reality | Air temperatures | Air quality | Odour | Multi sensory | Noise | EEG | Eye tracking (EOG) | Heart rate (HR) | ECG | Respiration (RSP) | Skin conductance response (SCR) | Blood pressure | Salivary alpha-amylase (sAA) | Electrodermal activity (EDA) | Satisfaction survey | Questionnaire | Survey | Self assessment software |
| Abbasi et al. | Combined effects of noise and air temperature on human neurophysiological responses in a simulated indoor environment | 2020 | - | 35 | | ● | | | | | ● | | | | ● | ● | ● | ● | ● | ● | | | | | | | | |
| Choi et al. | Development of the data-driven thermal satisfaction prediction model as a function of human physiological responses in a built environment | 2015 | 24 | 16 | ● | | | | | | ● | | | | ● | | | ● | | | ● | | | | ● | | | |
| Choi et al. | Measurement of occupants' stress based on electroencephalograms (EEG) in twelve combined environments | 2015 | 48 | 12 | ● | | | | | | ● | | ● | | ● | ● | | | | | | | | | | ● | | |
| Erkan | Examining wayfinding behaviours in architectural spaces using brain imaging with electroencephalography (EEG) | 2018 | 14 | 343 | ● | | | | | ● | | | | | | ● | | | | | | | | | | | | |
| Hakak et al. | Navigating abstract virtual environment: an eeg study | 2016 | 1 | 21 | ● | | | | ● | | | | | | | ● | | | | | | | | | | ● | | |
| Hollander et al. | Brain responses to architecture and planning: a preliminary neuro-assessment of the pedestrian experience in Boston, Massachusetts | 2016 | 29 | 5 | | | ● | | | | | | | ● | | ● | | | | | | | | | | | ● | |
| Kim et al. | Building occupants' psycho-physiological response to indoor climate and CO2 concentration changes in office buildings | 2020 | 6 | 22 | ● | | | | | | ● | ● | | | | | | | | | | ● | | | | ● | | |
| Li et al. | Building environment information and human perceptual feedback collected through a combined virtual reality (VR) and electroencephalogram (EEG) method | 2020 | 3 | 30 | ● | | | | | ● | | | | | | ● | | | | | | | | | | ● | | |
| Ma et al. | Emotion and novelty processing in an implicit aesthetic experience of architectures: evidence from an event-related potential study | 2015 | 11 | 17 | ● | | | ● | | | | | | | | | | | | | | | | | | | | |
| Sadeghi et al. | Using Neurology Sciences to Investigate the Color Component and Its Effect on Promoting the Sense of Spirituality in the Interior Space of the Vakil Mosque of Shiraz | 2019 | 10 | 14 | ● | | | ● | | | | | | | | ● | | | | | | | | | | | ● | |
| Saffarinia et al. | Effects of environmental design inspired by nature on psychological and physiological responses of clients in medical spaces | 2012 | 7 | 145 | | ● | | | | | | | | ● | | | | ● | | | | ● | | | | ● | | |
| Shan et al. | Neural-signal electroencephalogram (EEG) methods to improve human-building interaction under different indoor air quality | 2019 | 4 | 25 | | | ● | | | | ● | ● | | | | ● | | | | | | | | | | | | |
| Su et al. | A spatial filtering approach to environmental emotion perception based on electroencephalography | 2018 | 2 | 10 | ● | | | | ● | | | | | | | ● | | | | | | | | | | | | ● |
| Su et al. | Adolescents Environmental Emotion Perception by Integrating EEG and Eye Movements | 2019 | 2 | 12 | ● | | | | ● | | | | | | | ● | | | | | | | | | | | | ● |
| Sun et al. | Effects and interaction of different interior material treatment and personal preference on psychological and physiological responses in living environment | 2020 | 1 | 83 | | | ● | | | | | | | ● | | | | ● | | | | ● | ● | | | ● | | |
| Vijayan et al. | Probing Phenomenological Experiences Through Electroencephalography Brainwave Signals In Neuroarchitecture Study | 2019 | 5 | 4 | | | ● | | | | | | | ● | | ● | | | | | | | | | | | | |
| Westwood et al. | EEG Alpha Asymmetry in Virtual Environments for the Assessment of Stress-Related Disorders | 2012 | - | - | ● | | | | | ● | | | | | | ● | | | | | | | | | | | | |
| Zhang et al. | Human physiological responses to wooden indoor environment | 2017 | 21 | 20 | | ● | | | | | | | | ● | | | | | ● | | ● | ● | | | | | | |




* Duplicates (found in initial search)
Citation chasing was conducted for systematic review, *The emotional impact of built interior environments objectively measured by electrical activity (EEG) and subjective assessments: A systematic review* by using Google Scholar (forward citation chasing)

Article information (Forward citation chasing) 10.04.2021

| | | | | | Environment | | | Stimuli | | | | | | | | Obj. messures | | | | | | | | | | Sub. messures | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Author | Title | Year | Cited* | Part.** | Laboratory | Naturalistic | Natural | Images | Video | Virtual reality | Air temperatures | Air quality | Odour | Multi sensory | Noise/ audio | EEG | Eye tracking (EOG) | Heart rate (HR) | ECG | Respiration (RSP) | Skin conductance response (SCR) | Blood pressure | fMRI | Electrodermal activity (EDA) | Satisfaction survey | Questionnaire | Survey | Self report |
| Coburn et al. | Psychological and neural responses to architectural interiors | 2020 | 13 | 798 | ● | | | ● | | | | | | | | | | | | | | | ● | | | | ● | |
| Habibabad et al. | Recording the Users' Brain Waves in Manmade Religious Environments Based on Psychological Assessment of Form in Creation/Enhancement of Spiritual Sense | 2020 | - | 45 | ● | | | ● | | | | | | | | ● | | | | | | | | | | | ● | |
| Li et al. | Building environment information and human perceptual feedback collected through a combined virtual reality (VR) and electroencephalogram (EEG) method | 2020 | 3 | 30 | ● | | | | | ● | | | | | | ● | | | | | | | | | | ● | | |
| Lipson-Smith et al. | Exploring colour in context using Virtual Reality: Does a room change how you feel? | 2020 | - | 786 | ● | | | | | ● | | | | | | | | | | | | | | | | | ● | |
| Sadeghi et al. | Examination of the psychological impact and brainwaves functioning of the users of buildings and environments built based on promoting relaxation and spiritual sense | 2020 | 2 | 15 | ● | | | | | ● | | | | | | ● | | | | | | | | | | | | |
| Stolz et al. | Threat-conditioned contexts modulate the late positive potential to faces—A mobile EEG/ virtual reality study | 2019 | 11 | 25 | ● | | | | | ● | | | | | ● | ● | | | | | | | | | | | | ● |
| Vijayan et al. | Probing Phenomenological Experiences Through Electroencephalography Brainwave Signals In Neuroarchitecture Study | 2019 | 5 | 4 | | | ● | | | | | | | ● | | ● | | | | | | | | | | | | |




* Citation chasing was conducted for systematic review, *The emotional impact of built interior environments objectively measured by electrical activity (EEG) and subjective assessments: A systematic review* by reviewing the citations (backwards citation chasing)

Article information (Forward citation chasing) 10.04.2021

| Author | Title | Year | Cited* | Part.** | Environment | | | Stimuli | | | | | | | | Obj. messures | | | | | | | | | Sub. messures | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Laboratory | Naturalistic | Natural | Images | Video | Virtual reality | Air temperatures | Air quality | Odour | Multi sensory | Noise/ audio | EEG | Eye tracking (EOG) | Heart rate (HR) | ECG | Respiration (RSP) | Skin conductance response (SCR) | Blood pressure | fMRI | Electrodermal activity (EDA) | Satisfaction survey | Questionnaire | Survey | Self report |
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| Habibabad et al. | Recording the Users' Brain Waves in Manmade Religious Environments Based on Psychological Assessment of Form in Creation/Enhancement of Spiritual Sense | 2020 | - | 45 | ● | | | ● | | | | | | | | ● | | | | | | | | | | | ● | |
| Li et al. | Building environment information and human perceptual feedback collected through a combined virtual reality (VR) and electroencephalogram (EEG) method | 2020 | 3 | 30 | ● | | | | | ● | | | | | | ● | | | | | | | | | | ● | | |
| Lipson-Smith et al. | Exploring colour in context using Virtual Reality: Does a room change how you feel? | 2020 | - | 786 | ● | | | | | ● | | | | | | | | | | | | | | | | | ● | |
| Sadeghi et al. | Examination of the psychological impact and brainwaves functioning of the users of buildings and environments built based on promoting relaxation and spiritual sense | 2020 | 2 | 15 | ● | | | | | ● | | | | | | ● | | | | | | | | | | | | |
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| Vijayan et al. | Probing Phenomenological Experiences Through Electroencephalography Brainwave Signals In Neuroarchitecture Study | 2019 | 5 | 4 | | | ● | | | | | | | ● | | ● | | | | | | | | | | | | |

Article information (articles previously known to author)

| Author | Title | Year | Cited* | Part.** | Environment: Laboratory | Naturalistic | Natural | Stimuli: Images | Video | Virtual reality | Air temperatures | Air quality | Odour | Multi sensory | Noise/ audio | Obj. messures: EEG | Eye tracking (EOG) | Heart rate (HR) | ECG | Respiration (RSP) | Skin conductance response (SCR) | Blood pressure | Salivary alpha-amylase (sAA) | Electrodermal activity (EDA) | Sub. messures: Satisfaction survey | Questionnaire | Survey | Self assessment software |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Abd-Alhamid et al. | Evaluating the impact of viewing location on view perception using a virtual environment | 2020 | 4 | 28 | ● | | | | | ● | | | | | | | | ● | | | ● | | | | | ● | | |
| Banaei et al. | Walking through Architectural Spaces: The Impact of Interior Forms on Human Brain Dynamics | 2017 | 57 | 15 | ● | | | | | ● | | | | | | ● | | | | | | | | | | ● | | |
| Chamilothori et al. | Subjective and physiological responses to façade and sunlight pattern geometry in virtual reality | 2019 | 27 | 72 | ● | | | | | ● | | | | | | | | ● | | | ● | | | | | ● | | |
| Ergan et al, | Quantifying Human Experience in Architectural Spaces with Integrated Virtual Reality and Body Sensor Networks | 2019 | 33 | 33 | ● | | | | | ● | | | | | | ● | | ● | | | ● | | | | | | ● | |
| Higuera-Trujillo et al. | Multisensory stress reduction: a neuro-architecture study of paediatric waiting rooms | 2020 | 9 | 24 | ● | | | | | ● | | | | ● | | ● | | ● | | | | | | ● | | ● | | |
| Leite et al. | Physiological Arousal Quantifying Perception of Safe and Unsafe Virtual Environments by Older and Younger Adults | 2019 | 6 | 87 | ● | | | | | ● | | | | | | | | | ● | | | | | ● | | ● | | |
| Yin et. al | Effects of biophilic interventions in office on stress reaction and cognitive function: A randomized crossover study in virtual reality | 2019 | 25 | 30 | | | | | | ● | | | | | | | | ● | | | ● | ● | | | | ● | | |
| Zhou et al. | Influence of the Acoustic Environment in Hospital Wards on Patient Physiological and Psychological Indices | 2020 | - | 70 | ● | | | | | ● | | | | | ● | | | ● | | | ● | | | | | | ● | |

Article information (After final filtration) 16.04.2021

Article information (initial search)

| | | |
|---|---|---|
| Li et al. | Building environment information and human perceptual feedback collected through a combined virtual reality (VR) and electroencephalogram (EEG) method | 2020 |
| Sadeghi et al. | Using Neurology Sciences to Investigate the Color Component and Its Effect on Promoting the Sense of Spirituality in the Interior Space of the Vakil Mosque of Shiraz | 2019 |
| Shan et al. | Neural-signal electroencephalogram (EEG) methods to improve human-building interaction under different indoor air quality | 2019 |
| Su et al. | Adolescents Environmental Emotion Perception by Integrating EEG and Eye Movements | 2019 |
| Banaei et al. | Walking through Architectural Spaces: The Impact of Interior Forms on Human Brain Dynamics | 2017 |
| Ergan et al, | Quantifying Human Experience in Architectural Spaces with Integrated Virtual Reality and Body Sensor Networks | 2019 |
| Higuera-Trujillo et al. | Multisensory stress reduction: a neuro-architecture study of paediatric waiting rooms | 2020 |
| Coburn et al. | Psychological and neural responses to architectural interiors | 2020 |
| Shemesh et al. | Affective response to architecture–investigating human reaction to spaces with different geometry | 2017 |
| Vartanian et al. | Architectural design and the brain: Effects of ceiling height and perceived enclosure on beauty judgments and approach-avoidance decisions | 2015 |
| Vecchiato et al. | Electroencephalographic Correlates of Sensorimotor Integration and Embodiment during the Appreciation of Virtual Architectural Environments | 2015 |

| Author, year of publication | Participants | | | | | | Experiment environment | Test setting | Stimuli | Objective measurement (EEG) | Subjective assessment | | Findings | | | Independent variables |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | F | M | Total | Age | | Group characteristics | | | | | Tool | Purpose | Neurological | Emotional | Conclusion | |
| | | | | Mean | SD | | | | | | | | | | | |
| Banaei et al., 2017 | 8 | 7 | 15[a] | 28.6 | 2.6 | No education in architecture | Laboratory | VR | Walking through interior residential room | EEG: 128 electrodes | SAM test | Record pleasure, arousal, and dominance scale. | A strong impact of curvature geometries on activity in the ACC. Theta band activity in ACC correlated with specific feature types and geometry. | Lower pleasure and arousal ratings in linear geometries, higher in rooms with curvature geometries | An involvement of the ACC in processing architectural features beyond their emotional impact. | Interior spaces with different architectural forms |
| Ergan et al., 2019 | 11 | 22 | 32[b] | NR[1] | 0.19 | NR | NR | VE | Navigating through a educational facility | EEG: 14 channels | Self-report survey | Measure stress and anxiety | The positively configured environment was stress reducing compared with the negative environment. | Subjects felt more pleasant, focused and relaxed in the positively configured environment | The positive environment creates less stress and anxiety | Environments with different luminance, daylight, colour surfaces, outside view |
| Higuera-Trujillo et al., 2020 | 11 | 13 | 24[c] | 37 | 3.99 | Fathers or mothers of children in the paediatric service | Laboratory | VR | Observing waiting rooms | EEG: 9 channels | Stress self-assessment, State-Trait Anxiety Inventory | Measure stress and anxiety | Stress reduction due to all combinations of environmental satisfaction sources is evident | Visual, auditory and olfactory elements effects stress levels | A combination of environmental satisfaction sources reduces stress | Replicas of paediatric waiting rooms with different visual, auditory and olfactory |
| Li et al., 2020 | 15 | 15 | 30 | NR[3] | NR | University students | Laboratory | VR | Observing natural, semi-open, and closed spaces | EEG: 32 points | Face-to-face questionnaire | Determine subjects psychological changes in different scenarios | B-rhythms are related to satisfaction with human spatial perception, b-rhythms promote work efficiency | Subjective satisfaction depending on environment | Work efficiency is effected by the physical environment | 360° images of open natural, semi-open, and closed spaces |
| Vecchiato et al., 2015 | 5 | 12 | 17 | 26.8 | 2.4 | Not familiar with the IVR experience | Laboratory | VE | Observing bedrooms | EEG: 19 electrodes/ 24 channels | Questionnaires | Measure familiarity, novelty, comfort, pleasantness, arousal, and presence | It is possible to measure EEG correlates of architectural perception involving the cerebral circuits of sensorimotor integration, spatial navigation, and embodiment | Pleasantness were positively correlated with both novelty and arousal. Novelty were negatively correlated with familiarity | An involvement of motor and cognitive processes for the evaluation of architectural environments | Bedrooms with different furniture |

NR = Not reported
EEG = Eectroencephalogram

[1]Age range between 21 and 30 years old
[2]Visual, auditory and olfactory stimulation
[3]Age range between 18 and 25 years old
[4]Age range between 20 and 35 years old

| Citation | EEG parameters and conditions used | | | | | | | | | | Other recordings |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Brand | Device | Data processing software | Mobile/ non-moblie testing device | Electrode/ channels | Data filter | | Impedance | Movement allowed | Electrode layout | |
| | | | | | | Sampling rate | Band-pass filter | | | | |
| Banaei et al. | EASYCAP | NR | EEGLAB toolbox | Mobile | 128 electrodes | 1000 Hz | Hp = 0.016 Hz Lp = 250 Hz | <15 kΩ | YES | 5% system | NR |
| Ergan et al, | EMOTIV* | EPOC* | NR | Mobile | 14 channels | 128 Hz | Hp = 0.5 Hz Lp = 50 Hz | NR | Some | International 10–20 system | GSR (SCR), PPG (HRV) |
| Higuera-Trujillo et al. | Advanced Brain Monitoring | B-Alert x10 | EEGLAB via Matlab | Mobile | 9 channels** | 256 Hz | Hp = 0.5 Hz Lp = 40 Hz | NR | NO | NR | EDA, HRV |
| Li et al. | NR | NR | NR | NR | 32 electrodes | NR | NR | NR | Some*** | NR | NR |
| Vecchiato et al. | | | EEGLAB via BEMicro, EBNeuro | Mobile | 19 electrodes 24 channels | 256 Hz | Hp = 0.5 Hz Lp = 45 Hz | <10 kΩ | Some*** | NR | EDA, HR, SCL |

NR = Not reported
EDA= ElectrodermalActivity
HR= Heart Rate
HRV = Heart rate variability
GSR = Galvanic Skin Response
SCR = Skin Conductance Response
PPG = Photoplethysmography
SCL = Skin Conductance Level
EEG = Eectroencephalogram

*Not mentioned in article, but recognised by author (https://www.emotiv.com) (Figure 3(b) body area sensors used for bodily state data collection)
**Not mentioned in article, information found on Website (www.advancedbrainmonitoring.com)
***Only head

| Citation | Environment setting | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Method of experience | | Justification of environment | Lighting | Temperature | Smell | Noise | Space(s) | | | | | |
| | Devices | Software | | | | | | W x L x H | Software | Characteristics | Cluster | Differences | Settings |
| Banaei et al. | Head-mounted VR display (HTC Vive) and HMD controller | Unity game engine software | | NR | NR | NR | NR | 5 x 7.5 x 3m | Autodesk's 3DS | White interior colour, identical lighting | 17 + 1* | Form features | 69 |
| Ergan et al, | Touch screen, Apex controller (Vicon Motion Systems) and 3D goggles | Unity game engine software | | VE1: sufficient amount** VE2: below average | NR | NR | NR | NR | BIM | Rendered materials and lighting configurations | NR | Luminance, natural daylight, surface colour, openness of spaces, visual cues | 2 |
| Higuera-Trujillo et al. | Head-mounted VR display (HTC Vive) | NR | Paediatric waiting rooms are used by the general public and causes high levels of stress in children and their companions | NR | NR | Different scents | Different noises | NR | NR | Replica of the real paediatric waiting room | 19 | Visual, auditory and olfactory | 4 |
| Li et al. | VR helmet | Unity game engine software | | Natural and/or artificial | Average: 20.9°C (all trials) | NR | Different noises | NR | 360° panoramic camera | 360° images of open natural, semi-open library, and closed basement spaces. | NR | Visual, auditory | 3 |
| Vecchiato et al. | 3D images displayed on Viewsonic projectors using Nvidia 3D vision wireless glass | CAVE system | | NR | NR | NR | NR | 3 × 3 × 2.5m | Autodesk's 3DS Max 2011 | 3D images of bedrooms | NR | Interior design (furniture) | 3 |

NR = Not reported
BA = Below average
VE1 = Positive virtual environment
VE2 = Negative virtual environment

* One cubic room without significant form features was added as comparison room
** VE1: Luminance - above average (>3.5), Natural daylight - sufficient amount
VE2: Luminance - below average, natural daylight - less than sufficient amount

<table>
<tr><th rowspan="3">Citation</th><th colspan="14">Process</th></tr>
<tr><th rowspan="2">Material informed by previous study</th><th colspan="2">Research prior to the main study</th><th colspan="10">Main study procedure</th><th rowspan="2">Number of trials per experiment</th></tr>
<tr><th>Method</th><th>Purpose</th><th colspan="4">Pre-experiment</th><th colspan="5">Experiment</th><th>After</th></tr>
<tr><td>Banaei et al.</td><td>Banaei et al., 2017*</td><td>SAM ratings</td><td>Select clusters</td><td>Reading the instructions</td><td colspan="3">VR demonstration, placement of device, 10min</td><td>Basic room, 5 sec** (not moving)</td><td>Block# - Room# 1-17 (moving)</td><td>Virtual SAM test</td><td colspan="2">Stroop test, 5sec</td><td>Questionnaire, 9-point Likert scale (-4 to 4)</td><td>4 blocks of 18 room trials, each room contain 3 perspective trials, 10 mins break after block 2 and 4</td></tr>
<tr><td>Ergan et al,</td><td>NR</td><td>Literature review</td><td>Select design features</td><td>Get familiarise with the set up and tools</td><td>Initial virtual walkthrough, 7min</td><td colspan="2">Preparation of subject for biometric sensors</td><td>Capture EEG, GSR & PPG baseline, 2min (not moving)</td><td>VE1 or VE2, 7mins (moving)</td><td>Resting 2min</td><td colspan="2">VE1 or VE2, 7min (moving)</td><td>Self-report survey, 3min</td><td>2 trials: VE1 and VE2</td></tr>
<tr><td>Higuera-Trujillo et al.</td><td>NR</td><td>Literature review, questionnaire</td><td>Select environmental satisfaction sources</td><td>Basic instructions, Placement of neurophysiology devices, 10min</td><td>Record EEG, EDA & baseline, 4min</td><td>Stress setting task, 1mins</td><td>Instructions, 2min</td><td>Preparation audio, 2min</td><td>Stressor Arithmetic tasks, 2min</td><td>Stressor verification, 0,5min</td><td colspan="2">CESS#, 2min</td><td>Assessment of experience, 5min</td><td>4 trials: 4 CESS configurations</td></tr>
<tr><td>Li et al.</td><td>NR</td><td>Analysis of a significant number of image samples</td><td>Select scenes</td><td>Putting on instruments and equipment</td><td colspan="2">Rest with eyes closed, 30sec</td><td>Scene adaptation, 4 min</td><td>Subjective questionnaire survey</td><td>Stroop test</td><td>Digital calculation experiment</td><td>Meaningless figure recognition experiment</td><td>Symbolic digital simulation experiment</td><td>Post-experiment evaluation</td><td>3 trials: 3 scenes</td></tr>
<tr><td>Vecchiato et al.</td><td>NR</td><td>NR</td><td>NR</td><td colspan="3">Familiarization period, neutral environment</td><td>Verbally describe the virtual scenario</td><td colspan="5">Visually explore the surrounding environment</td><td>Questionnaires, verbally express judgment, 2min</td><td>3 trails: 3 VEs</td></tr>
</table>

* Banaei, M., Ahmadi, A., and Yazdanfar, A. (2017). Application of AI methods in clustering of architecture interior forms. Front. Arch. Res. 6, 360–373.

**Cubic room without significant form features

# Previously published systematic reviews

| Topic | Title | Discription |
|---|---|---|
| How does the built environment influence human experience | **The Enactive Approach to Architectural Experience: A Neurophysiological Perspective on Embodiment, Motivation, and Affordances** | Examine the existing literature systematically to explain the influence of the built environment on human experience by using approaches from neuroscience by examining the conceptualizations in the field. |
| How does interior spaces impact human emotions | **Impact of built environment design on emotion measured via neurophysiological correlates and subjective indicators: A systematic review** | The evidence on the impact of the design of interior spaces on human emotion. |
| Human emotional responses to VR | **Emotion Recognition in Immersive Virtual Reality: From St+C5atistics to Affective Computing** | The emotion recognition research undertaken with physiological and behavioural measures using head-mounted displays as elicitation devices. |
| Neurophysiological and biometric instruments | **Review of the use of neurophysiological and biometric measures in experimental design research** | Analyze and classifie neurophysiological and biometric instruments, the kind of stakeholders involved and the supported design research activities. |
| Emotons and controlled environments | **The Impact of Moving through the Built Environment on Emotional and Neurophysiological State - A Systematic Literature Review** | Find and synthesize recent relevant studies. Investe the impact of other visuo-spatial stimuli on emotions in a rigorous way. |
| How does the built environment influence human experience | **A critical review on the impact of built environment on users' measured brain activity** | The impact of the built environment on the user's state of mind, with a focus on the measured brain activities to indicate the momentary state of mind. |
| Human behaviour research | **Creating Spaces that Understand People: Employing Sensor Technologies to Inform the Design and Operation of Human-centred Spaces** | The role that sensor-enabled human behaviour research can play in the creation of human-centred spaces. |
| The relationship between users' spatial, environmental and psychological experiences | **Conceptual Parametric Relationship for Occupants' Domestic Environmental Experience** | Exploration of the theoretical relationship between spatial and environmental design factors within domestic settings |
| Pleasure induced by music and visual-art | **Constituents of Music and Visual-Art Related Pleasure – A Critical Integrative Literature Review** | Identify which themes and processes emerged as key features for conceptualizing art-induced pleasure. |
| Biophilic design on university settings | **Biophilic Design for Restorative University Learning Environments: A Critical Review of Literature and Design Recommendations** | Identify pertinent themes in published multi-disciplinary literature relating to the influence of the built environment |
| The neurobiological effects of virtual reality | **Virtual Reality for Neu-rorehabilitation and Cognitive Enhancement** | The utility of different types of virtual reality for providing controllable, safe environments. |
| How does the built environment influence human experience | **Brain activity, underlying mood and the environment: A systematic review** | How different environments affect brain activity and associated mood response. |

# Appendix C: Reviewed articles

frontiers in Human Neuroscience

ORIGINAL RESEARCH
published: 27 September 2017
doi: 10.3389/fnhum.2017.00477

# Walking through Architectural Spaces: The Impact of Interior Forms on Human Brain Dynamics

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Neuroarchitecture uses neuroscientific tools to better understand architectural design and its impact on human perception and subjective experience. The form or shape of the built environment is fundamental to architectural design, but not many studies have shown the impact of different forms on the inhabitants' emotions. This study investigated the neurophysiological correlates of different interior forms on the perceivers' affective state and the accompanying brain activity. To understand the impact of naturalistic three-dimensional (3D) architectural forms, it is essential to perceive forms from different perspectives. We computed clusters of form features extracted from pictures of residential interiors and constructed exemplary 3D room models based on and representing different formal clusters. To investigate human brain activity during 3D perception of architectural spaces, we used a mobile brain/body imaging (MoBI) approach recording the electroencephalogram (EEG) of participants while they naturally walk through different interior forms in virtual reality (VR). The results revealed a strong impact of curvature geometries on activity in the anterior cingulate cortex (ACC). Theta band activity in ACC correlated with specific feature types ($r_s$ (14) = 0.525, $p$ = 0.037) and geometry ($r_s$ (14) = −0.579, $p$ = 0.019), providing evidence for a role of this structure in processing architectural features beyond their emotional impact. The posterior cingulate cortex and the occipital lobe were involved in the perception of different room perspectives during the stroll through the rooms. This study sheds new light on the use of mobile EEG and VR in architectural studies and provides the opportunity to study human brain dynamics in participants that actively explore and realistically experience architectural spaces.

**Keywords: neuroarchitecture, EEG, mobile brain/body imaging (MoBI), architectural interior form, virtual reality, HMD**

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## INTRODUCTION

In recent years, advancements in neuroscientific methods have made it possible to study the influence of different architectural styles on human perception and affective states. The field of neuroarchitecture studies the effects of the built environment on its inhabitants by using neuroscientific tools (Edelstein, 2008; Nanda et al., 2013). Historically, architectural studies were based on philosophical constructs or analysis of behavioral patterns to relate human responses to the design under investigation (Edelstein and Macagno, 2012, p. 28). While such approaches provide descriptive evidences, they cannot clearly specify the reasons for different behaviors in built environments. Of late, neuroscientific studies have been attempting to fill the gap between architecture and psychology by describing some of the underlying mechanisms that explain how differences in architectural features cause behavioral outcomes (Vartanian et al., 2013). Several neuroarchitectural studies have investigated different architectural styles (Choo et al., 2017), embodiment (Vecchiato et al., 2015), contours (Vartanian et al., 2013), height and enclosure (Vartanian et al., 2015), built vs. natural environment (Roe et al., 2013; Banaei et al., 2015), lighting (Shin et al., 2014), color (Küller et al., 2009), or the impact of the built environment on human memory (Sternberg, 2010, p. 147).

The present study focused on the form of interior places and its impact on the human perceiver. The Oxford Dictionary defines "form" as "the visible aspect of a thing; the shape or figure of the body as distinguished from the face" (OED, 2016). The form is one of the main aspects in architectural design and deciding which forms to use is one of the most challenging aspects of the design process (Madani Nejad, 2007, p. 3). While architects are responsible for considering the function and technology of their design, they are mostly free in designing the form according to their personality and individual preferences (Ackerman et al., 2017). To find a more objective approach to describe forms and their impact on the inhabitant, this study built a framework to design forms based on a data-driven approach using cluster analysis of form features and neuroscientific methods to evaluate the impact of form on human perceivers. In this "neuroscience of the experience of architecture" (Robinson and Pallasmaa, 2015, p. 82) study, we focused on the emotional impact of different interior forms on inhabitants, as affective responses toward environments are accrued automatically and unconsciously (Coburn et al., 2017).

A few studies investigated the relationship between architectural form and emotion (Bar and Neta, 2006; Madani Nejad, 2007; Shemesh et al., 2017). Some of these studies sought to define curved lines with adjectives like "serene", "graceful", and "tender-sentimental", and described angles as "robust", "vigorous" and "somewhat more dignified" (Lundholm, 1921; Poffenberger and Barrows, 1924; Hevner, 1935). Roelfsema et al. (1999) concluded that having too many curved forms could cause stress. Neuroscientific approaches using imaging methods like functional magnetic resonance imaging (fMRI) showed that people preferred curved interior forms over rectilinear forms and that perception of the former was associated with increased activity within the anterior cingulate cortex (ACC; Vartanian et al., 2013). The authors further demonstrated the involvement of anterior mid cingulate cortex in approach-avoidance decisions for enclosed rooms (Vartanian et al., 2015). Other fMRI studies investigating the relationship of object forms with emotional experience demonstrated the activation of the amygdala by sharp contoured objects (Bar and Neta, 2007; Ghoshal et al., 2016, p. 102). The parahippocampal place area (PPA) and the lateral occipital complex (LOC) play a general role in the perception of architectural styles (Choo et al., 2017). While the PPA is also active for shapes with rectilinear features (Nasr et al., 2014), the LOC is activated by shapes with curved features (Nanda et al., 2013) and the representation of object identity and location (Cichy et al., 2011). Moreover, visual cortex areas such as V1, V2, V3 and V3a are involved in three-dimensional (3D) shape perception (Welchman et al., 2005). However, despite the wealth of new insights from these imaging approaches, none of the studies used a quantitative method to describe forms and their role in architectural design. Most studies used only rectilinear and curvature forms as differentiating aspects (Dazkir, 2009; Nanda et al., 2013; Vartanian et al., 2013; Nasr et al., 2014).

According to a previous study, forms of built places are more complicated and contain more form features than curvature and rectilinear geometries (Banaei et al., 2017). A systematic analysis of living room interiors showed that real places combine different form features with different densities, and that the combination of different forms significantly shapes the interior. Cluster analysis of different forms revealed the main form features as linear solids, curved linear solids, and surfaces and rectangular Euclidean solids with different angles, locations, and scales as these play an important role in feature distinction. Most rooms contained rectangular forms, and the results revealed that linear solids were important for distinguishing between different rooms. The reality of built environments reveals a mixture of different forms. To understand the functional role of forms for the design process, we need to understand not only the effects of isolated forms on the perceiver, but also the impact of their combination. Therefore, this study used a combination of forms derived from formal cluster analysis of real built environments.

Besides a reduction to only a few architectural forms, almost all previous studies investigated the effect of forms on the perceiver using two-dimensional (2D) images. This stands in marked contrast to human experiences of architectural spaces in the real world, which is inherently 3D (Coburn et al., 2017). Recently, virtual reality (VR) technologies like CAVE environments were introduced to study the perception of 3D forms (Welchman et al., 2005). However, while the use of 3D stimulus material allowing rotation of the head and torso is a significant progress toward more realistic measures, these studies lack natural movement through the built environment (Vecchiato et al., 2015). It is essential to look around and see the places from different perspectives to allow a natural perception of the 3D environment. This is especially the case for the perception of 3D shapes. Just by navigating through the environment, our visual system can learn about our surroundings (Eagleman, 2015, p. 47). Movement is essential for an embodied perception of 3D environments (Gramann, 2013), hence the impact of architectural design on the moving inhabitant. Therefore, in this study, we allowed natural movement through the built environment using head-mounted VR displays (HMD VR) allowing exploration of 3D architectural spaces. The VR was combined with mobile brain/body imaging (MoBI) synchronously recording movement and brain dynamics during active exploration of the virtual environment (Gramann et al., 2014). To overcome the restrictions of traditional electroencephalography (EEG) studies, MoBI synchronizes recordings of brain dynamics in actively behaving participants with motion capture and other data streams, and uses data-driven analysis approaches to dissociate brain from non-brain sources of activity that underlie cognitive and affective changes during natural movement in the environment (Makeig et al., 2009; Gramann et al., 2010a, 2011; Gwin et al., 2010; Gwin, 2012; Jungnickel and Gramann, 2016).

Combining MoBI with VR allows researchers to study the designed environment and its impact on human experience even before construction. Moreover, investigating the brain dynamics using EEG provides unobtrusive insights into the cognitive and affective processing of the human in the environment with adequate temporal resolution. Although fMRI and functional near-infrared spectroscopy (fNIRS) provide a spatial resolution to describe the brain areas involved in the processing of the architectural and urban design (Tsunetsugu et al., 2005; Vecchiato et al., 2015; Choo et al., 2017), these methods lack the high temporal resolution that cognitive processes reveal.

Since natural perception of the built environment is based on active movement leading to different 3D perspectives of the same, the aim of this study was to investigate the effects of different interior form features on human brain activity in participants naturally exploring the 3D space. Based on the results of previous imaging studies and previous subjective emotional ratings of materials used in our study, we expected significant differences in the perception of different architectural forms in brain regions relevant to shape processing and brain areas related to affective processes.

# MATERIALS AND METHODS

## Participants

Data was collected from 17 healthy right-handed volunteers with a mean age of 28.6 years (σ = 2.6). Two subjects were removed from the analysis because of technical problems during the EEG recordings and all reported results are based on the final group of 15 participants (8 females, 7 males). As architects and non-architects would have different reactions towards space (Kirk et al., 2009), we chose participants without prior education in architectural studies. All participants had normal or corrected to normal vision and none reported a history of neurological disease. Volunteers were compensated 10 Euro/h or received course credit for their participation. All participants provided written informed consent before the experiment and the study was approved by the local ethics committee of the Technische Universität Berlin according to the guidelines of the German Psychological Society.

## Experimental Design and Procedure

Based on the results of the previous study (Banaei et al., 2017), 25 different form clusters were extracted from 343 interior images of living rooms from different architectural epochs with varying architectural styles. The formal clusters, derived from high dimensional clustering based on internal and external similarity functions, led to different descriptive form features. Features' dimensions are 8 types, 13 geometries, 6 scales, 5 locations and 6 angles (Banaei et al., 2017). We chose the top five features of each cluster to build 3D models of rooms using Autodesk's 3Ds Max-student version (San Francisco, CA, USA) replicating the clusters' density of form features. Virtual rooms (W × L × H: 5.0 × 7.5 × 3.0 m) were built with white interior color and identical lighting. The only difference between the rooms was their form features. The unity game engine software (Unity Technologies, San Francisco, CA, USA)[1] was used to create the rooms and the tests in VR.

In the first study, we used a virtual self-assessment manikin (SAM; Bradley and Lang, 1994) test to select a subset of clusters for the EEG study. Seventy-five rooms were constructed with three rooms for each of the 25 clusters to represent rooms with form differences. Forty volunteers with a mean age of 27.6 years (σ = 4.7) participated in the study wearing a head-mounted display (HMD-Gear VR) to evaluate the 75 rooms with respect to their emotional impact. Participants provided their responses while standing. One participant was removed from the study because of technical issues resulting in data from 21 female and 18 male participants.

The obtained SAM ratings represented the subjective experience for each of the 75 rooms on the pleasure, arousal, and dominance scale. The scores provided information about the subjective experience of pleasure (+P) vs. displeasure (−P), arousal (+A) vs. non-arousal (−A), and dominance (+D) vs. submissiveness (−D). The 2P × 2A × 2D emotion categories of Russell and Mehrabian's PAD emotion model were used to divide rooms into different emotional groups (Mehrabian and Russell, 1974). To this end, each room was assigned to an emotional group according to its positive or negative rate in the pleasure, arousal, and dominance scales. The average scores for each dimension and room were computed and rooms with similar emotional ratings were grouped together. The results divided the 25 formal clusters into five groups that differed along the emotional model dimensions (+P +A −D, −P −A −D, −P +A −D, +P +A +D, and +P −A +D). To test whether the rooms in the different groups were significantly different in their emotional responses, three mixed measure ANOVAs with a 3 (rooms representing a cluster) × 5 (emotional groups) design for each of the dependent variables pleasure, arousal, and dominance were computed using Greenhouse-Geisser corrected values for the results with violations of sphericity. The results showed a significant main effect of the emotional groups on pleasure scores ($F_{(2.055,78.092)} = 29.992$; $p < 0.001$; $\eta^2 = 0.441$), arousal scores ($F_{(2.227,84.636)} = 11.577$; $p < 0.001$; $\eta^2 = 0.234$), and the dominance scores ($F_{(2.207,83.857)} = 18.732$; $p < 0.001$; $\eta^2 = 0.330$). None of the analyses revealed a significant impact of the rooms or an interaction effect (all $p$s $\geq 0.131$). Subsequently, the eight lowest ranked clusters were removed, resulting in a selection of 17 from the initial 25 clusters that used for further analysis. Besides these 17 clusters, one room was added to the study containing a simple cubic room without significant form features serving as comparison room.

In the following EEG study, for each of the selected 17 clusters, one additional room was constructed to increase the number of rooms to be tested in the EEG experiment. This resulted in four

[1] https://unity3d.com

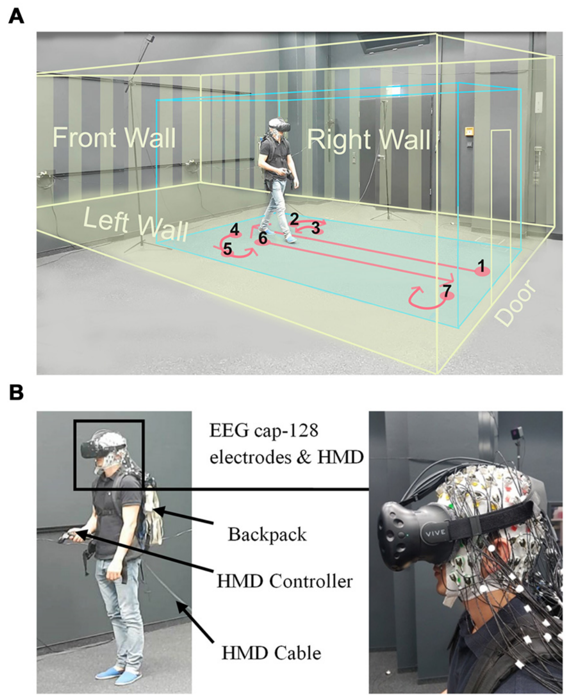


**FIGURE 1 |** Experimental setup. **(A)** Displays a participant while walking inside the laboratory wearing a head-mounted VR display (HTC Vive), the virtual room, and an electroencephalogram (EEG) cap. The participant provided written consent that the video recordings may be used in scientific publications. The blue box displays the borders of the walking space and the yellow box indicates the dimensions of the virtual room. The instructed walking paths are marked in red and all the walls and the door of virtual room are displayed in yellow. **(B)** Left: displays a participant wearing the head-mounted display (HMD; HTC Vive) and holding a controller in his hand. The EEG transmission systems were located in a backpack. The HMD cable was connected to the rendering PC and was extended to allow free movement of participants, Right: close view on the HMD place on an electrode cap with 128 actively amplified electrodes.

rooms with comparable feature densities, each for the 17 clusters of interest plus one room without features for comparison. This led to an overall number of 69 rooms presented in separate trials. Participants walked inside the different rooms with the HMD (HTC Vive) and an EEG cap (see **Figure 1**). After each room trial, the same virtual SAM test that was used in the first study was recorded. The SAM ratings were used as a factor for the later EEG analysis. Finally, the Stroop test (Stroop, 1935) was recorded at the end of each room trial to test whether the participants demonstrated comparable levels of attention and involvement with the task for all rooms.

## EEG Recording

The EEG was recorded from 128 active electrodes referenced to an electrode near CP1 with a sampling rate of 1000 Hz and band-pass filter from 0.016 Hz to 250 Hz (BrainAmps and Move System, Brain Products, Gilching, Germany). Electrodes were placed in an elastic cap (EASYCAP, Herrsching, Germany) using a custom layout with equidistant distribution of electrodes approximating the 5% system (Oostenveld and Praamstra, 2001). Electrode locations were recorded using an optical tracking system (Polaris Vicra, NDI, Waterloo, ON, Canada). Electrode impedance was kept below 15 kOhm in all electrodes.

## Motion Capture Recording

Two HTC Vive lighthouse cameras captured the movement of participants with a sampling rate of 75 Hz. The data stream containing the location (x, y and z), angles (x, y, z and w) and all the events of the virtual rooms and tests were produced by unity software (Unity Technologies, San Francisco, CA, USA) custom functions. All data streams, namely EEG, motion, and events from the experimental protocol were synchronized and recorded using the Lab Streaming Layer Software (Kothe, 2014).

## Procedure

After reading the instructions, participants entered a VR demonstration of how to use the HMD controller to answer the virtual questions and how to walk in VR, as shown in **Figure 2**. After about 10 min of practice, participants proceeded with the EEG recordings.

An experimental trial started with a *basic room* (complete cubic shape), with participants receiving an instruction not to move (a "Do Not Move" sign at eye level). The basic room was displayed for 5 s, followed by the presentation of one of the 69 experimental rooms. After the onset of the experimental room, participants were instructed to walk inside the room until they reached the border of the virtual room. They then turned 90 degrees to their right and faced the *right wall*. Afterward, they turned 90 degrees to their left and faced the *front wall*, followed by an additional turn of 90 degrees to the left to face the *left wall*. After one additional turn of 90 degrees to their left, the participants faced the entrance *door*. At that point, the participants walked back to the entrance door and turned 180 degrees to face the room again (see **Figure 1**). Participants were then presented with a virtual SAM test and had time to rate the room according to the pleasure, arousal, and dominance scale. The SAM test was followed by the two-color (red and green) virtual Stroop test, and participants had 5 s to provide as many correct answers as possible. After the Stroop test, the basic room with the "Do Not Move" sign appeared again for 5 s initiating the next trial. The experiment comprised four randomized blocks of 18 room trials each (17 clusters of interest plus one room without features) that each room contain three perspective trials. At the end of the second and fourth blocks, a sign ("The End") was displayed, meaning that the participants have a 10-min break or the end of experiment, respectively. After the experiment, the participants answered questions regarding their VR experience and their health conditions after the experiment.

## EEG Analysis

### EEG Data Preprocessing

The analysis was done using open source EEGLAB toolbox[2] (Delorme and Makeig, 2004) and custom MATLAB functions (The Mathworks, Inc., Natick, MA, USA). The data was filtered

[2]http://www.sccn.ucsd.edu/eeglab

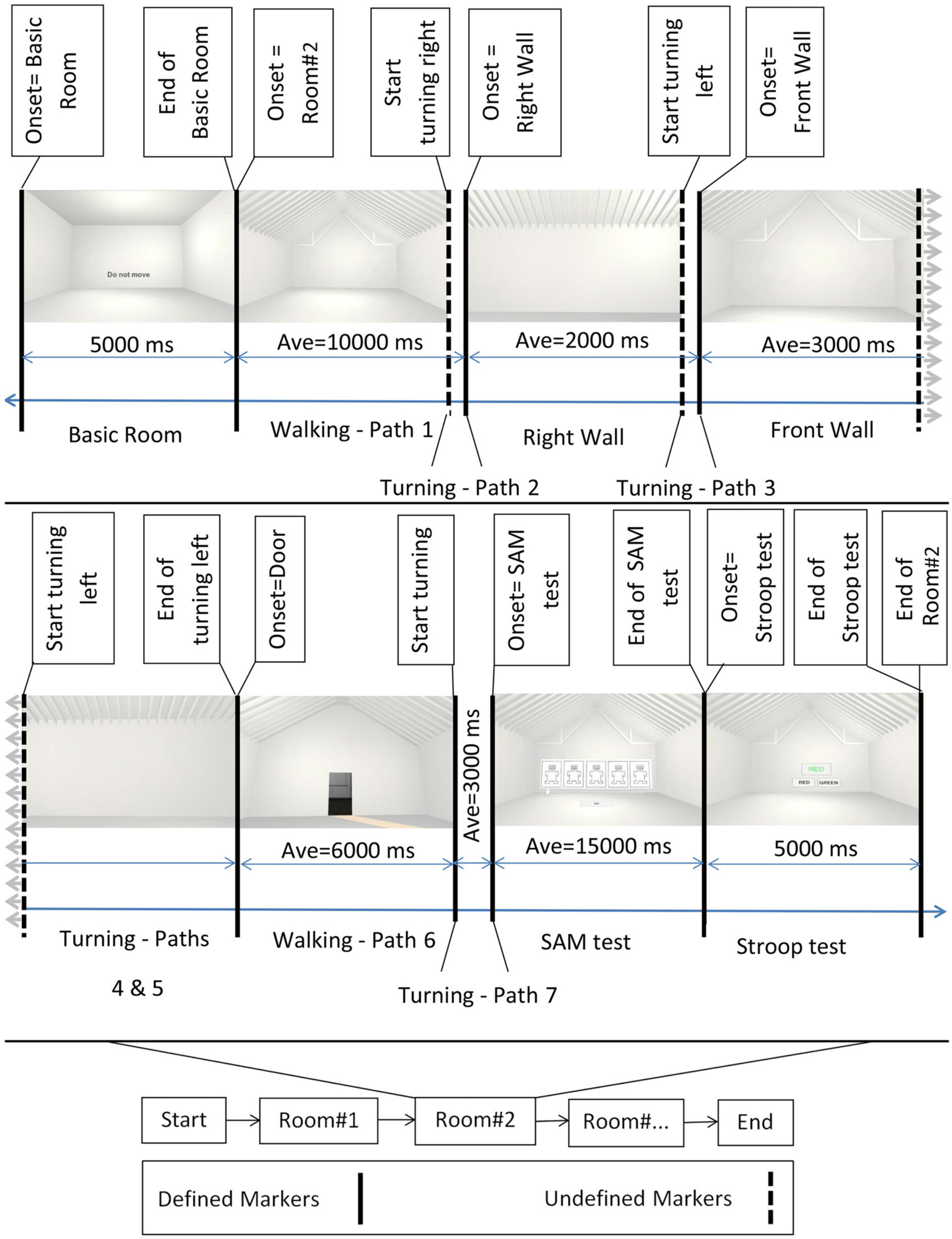


**FIGURE 2 |** Block diagram of the experiment. Bottom middle: the onset of the different rooms. Top: example of rooms' perspectives as participants perceived them while walking. First and then second row from left to right, after showing the Basic room for 5000 ms with a "Do Not Move" sign, the trial started and participants walked inside the virtual room. They then turned 90 degrees to their right and faced the *right wall*. Subsequently they turned 90 degrees to their left and faced the *front wall*, followed by an additional turn of 90 degrees to their left to face the *left wall*. After one additional turn of 90 degrees to their left, participants faced the entrance *door*. Then, participants walked back to the starting point (entrance door) and turned 180 degrees to face the room. At the end of each trial, the virtual self-assessment manikin (SAM) test and the Stroop test were shown. Defined markers describe events in the experimental protocol that were controlled and appeared at predefined time points during the experiment. These included, e.g., the onset of the basic room, the onset of the SAM test, etc. Undefined markers denote events that were not determined by the experimental protocol, i.e., the time point of some of the turnings depended on the individual preferred movement speed and viewing time. Sample room was created from Banaei et al. (2017).

using a high-pass filter (1 Hz) followed by a low-pass filter (100 Hz) and subsequent down sampling to 500 Hz. Periods in the raw signal containing artifacts were removed manually. Eye movements were not regarded as an artifact. Noisy channels were removed manually by visual inspection of the data and EEGLAB automatic channel rejection. On average, 99.3 EEG channels remained for further analyses (range: 80–122; σ = 14.04).

Independent component analysis (ICA) was computed using the EEGLAB runica function and the data was re-referenced to an average reference after ICA analysis. ICA analysis was used in mobile EEG studies to separate brain and non-brain activities (Gwin et al., 2010; Gramann et al., 2011, 2014). An equivalent dipole model was calculated for each IC using a boundary element head model (BEM) based on the MNI brain (Montreal Neurological Institute, MNI, Montreal, QC, Canada) as implemented by DIPFIT routines (Oostenveld and Oostendorp, 2002). Each model was aligned by adjusting its individually measured landmarks (nasion, inion, vertex and preauricular points) with the landmarks as implemented in the head model. ICs representing brain activity were selected from the overall 1490 ICs based on their spectra, location of their equivalent dipole model and the residual variance (<15%) of the corresponding dipole models. Dipoles placed outside of the head model were not further considered. In total, 305 ICs remained for all participants for further analysis with an average of 20.3 ICs per subject (range: 12–29, σ = 5.7).

The continuous EEG data was epoched into 1.2 s long epochs with the onset of events indicating different views into the rooms selecting the room onset, the front wall, and the right wall, including a 0.5 s pre-stimulus baseline. For a majority of participants, the instructed left turn to face the left wall did not allow to extract any peaks in quaternion numbers because it was indistinguishable from an ongoing 180 degree turn to the left. Although participants were instructed to wait for some seconds before turning towards the entrance, most participants did not wait long enough for meaningful epoch extraction. Thus, the analyses focused on three room perspectives including the room onset, the right wall, and the front wall. The average number of perspective trials for each room's perspective were 59.73 (σ: 11.14), 37.53 (σ: 13.37) and 56.2 (σ: 14.81) for room onset, right wall and front wall, respectively.

By using the EEGLAB pre-clustering function, distances between all ICs were calculated with the weighted measures of ERP, power spectrum, event-related spectral perturbations (ERSPs), inter-trial coherences (ITCs), the components' scalp maps, and their equivalent dipole model locations. Power spectrum was computed with fast fourier transform (FFT) and frequencies between 3–75 Hz were used for clustering. ERSP and ITC were calculated with 200 time points and 3-cycle wavelets (with a Hanning-tapered window applied). Principal component analysis (PCA) reduced the dimensions of all measures to the first 10 principle components, except dipole location with three dimensions. Measures were normalized, weighted, and combined into cluster position vectors. All the measures were weighted with the standard weighting of 1, except dipole locations ($w$ = 25) and ERSP ($w$ = 10) like in similar MoBI studies (Jungnickel and Gramann, 2016). Clustering was done by a K-means algorithm in EEGLAB with the number of clusters set to 24. ICs with a distance higher than 3 SDs to the mean of any cluster centroid were set as an outlier resulting in seven outlier ICs. In case clusters contained more than one IC from one participant, extra ICs were moved to the outlier cluster (53 ICs). The dipole location of cluster centroids were estimated based on the Talairach[3] software (Lancaster et al., 2000), providing approximate locations of the cluster centroids. Clusters including ICs from at least 60% of all participants were selected and ERSP results are reported for these clusters.

## Motion Capture Analysis

Motion capture data was used to find turning points in the trial sequence for each participant. The quaternion number (w) was analyzed to find the turning points using the peaks in the quaternion chart as an indicator. **Figure 3** displays changes in quaternion numbers for a representative walking path of one participant moving through the 34 rooms (A) with a closer look on the path for one room (B).

# RESULTS

The participants' presence in VR was measured after the experiment with a questionnaire in 9-point Likert scale (−4 to 4). Analyzing the result with a one-sample $t$-test ($p < 0.05$) showed that the virtual environment appeared real to the participants ($\bar{x}$ = 1.07; σ = 1.38). Participants had the feeling that the virtual environment surrounded them ($\bar{x}$ = 1.14; σ = 1.23) and they did not have the feeling to see only images ($\bar{x}$ = −0.78; σ = 1.52). Furthermore, the virtual world did not seem more real than the real world ($\bar{x}$ = −1.57; σ = 1.55) and participants felt presence in virtual space ($\bar{x}$ = 1, σ = 1.24). In summary, the data revealed that the designed virtual environment was adequate to support a feeling of being in a real environment.

## SAM Ratings

The virtual SAM test was used to assess the experienced emotional impact of the formal clusters (17 clusters) to be used for further EEG analyses. Participants rated each room according to the pleasure, arousal, and dominance scale after strolling through the rooms. The mean of the three scales for each formal cluster was calculated and formal clusters with similar emotional categories were grouped based on the 2P × 2A × 2D emotion categories of Mehrabian and Russell (1974) PAD emotion model (see "Experimental Design and Procedure" Section). The results revealed two groups of +P −A +D (Group 1) and +P +A +D (Group 2). Ten of the 17 formal clusters were categorized as Group 1 and seven formal clusters as Group 2. The emotional categories of the simple cubic comparison room was +P −A +D (pleasure: $\bar{x}$ = 5.05, σ = 1.72, arousal: $\bar{x}$ = 3.93, σ = 2.25, and dominance: $\bar{x}$ = 5.80, σ = 2.10) which was sorted into Group 1. As this room was not rated as emotionally neutral, we did not use it as a baseline for the EEG analyses. Three mixed measure ANOVAs with a 4 (rooms per cluster) × 2 (emotional rating groups) design for each of the dependent variables pleasure,

[3]http://www.talairach.org/

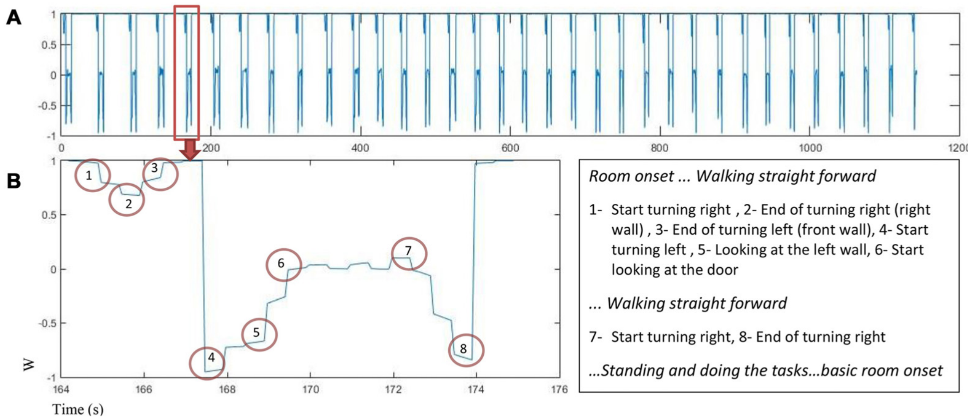


**FIGURE 3 |** The quaternion number changes as a function of time for one participant **(A)** *w* value for 34 rooms in about 1200 s. **(B)** Left: *w* changes in one room while participant is walking and turning, the turning points are marked, Right: turns marker description.

arousal, and dominance were computed to test for the significant differences between the two groups. The Greenhouse-Geisser correction was used wherever there was a violation of sphericity. The results revealed a significant differences in the two emotion categories for pleasure scores ($F_{(1,14)} = 10.692$; $p = 0.006$; $\eta^2 = 0.433$) and arousal scores ($F_{(1,14)} = 8.423$; $p = 0.012$; $\eta^2 = 0.376$). There was no significant effect of grouping for the dominance scale ($p = 0.128$) and no significant effect of rooms per cluster for pleasure, arousal, and dominance scale (all $ps \geq 0.055$). Also, there was no interaction effect for all three ANOVAs (all $ps \geq 0.307$). The *post hoc* test showed that Group 2 had higher scores in both pleasure and arousal scales ($p = 0.006$). A Spearman's rank-order correlation was calculated to assess the relationship between SAM ratings in the first and the main study. The results revealed significant positive correlations between SAM ratings in the two studies for the pleasure scale ($r_s$ (17) = 0.621, $p = 0.008$) and the arousal scale ($r_s$ (17) = 0.687, $p = 0.002$). There was no significant correlation of ratings in the dominance scale between the two studies ($p = 0.075$). Based on the missing differences in the dominance ratings, we focused on the pleasure and arousal dimensions for further analysis.

## Form Features

According to the SAM scales, 17 formal clusters were divided into two groups differing in the pleasure and the arousal scale. Each form feature defines different aspects of the space providing a location, scale, angle, type and geometry (Banaei et al., 2017). As an example, consider a simple cube (type) with Euclidian geometry placed in an empty room; the room itself consists of six surfaces (type) and 12 edges (type) that have one-dimensional (1D) linear and 2D rectangular geometry with orthogonal angles. The room will appear differently if the cube is positioned on the central wall as compared to the ceiling (location) and whether the cube is small or big (scale). The cube's angle can be towards or against the basic room XYZ-axis.

An independent-samples $t$-test was conducted to compare the form features' density in the two emotion rating groups (Group 1: Low pleasure and arousal and Group 2: high pleasure and arousal) regarding location, object to object scale, object to context scale, Z-axis angle, XY-axis angle, type and geometry. There was a significant differences in 1D linear geometries between Group 1 ($\bar{x} = 0.82$, σ = 0.12) and Group 2 ($\bar{x} = 0.44$, σ = 0.36; $t_{(6.909)} = 2.70$, $p = 0.031$). Also, there were significant differences in the sum of linear geometry densities (1D, 2D and 3D) between Group 1 ($\bar{x} = 0.99$, σ = 0.009) and Group 2 ($\bar{x} = 0.58$, σ = 0.40; $t_{(6.004)} = 2.74$, $p = 0.034$), and in the sum of curvature geometry densities (1D, 2D and 3D) between Group 1 ($\bar{x} = 0.001$, σ = 0.003) and Group 2 ($\bar{x} = 0.43$, σ = 0.43; $t_{(6)} = -2.62$, $p = 0.039$). Therefore, the main differences between the two groups were in the linear and curvature geometries (see **Figure 4**).

## SAM Rating and Form Features Correlation

A Spearman's rank-order correlation was computed to assess the relationship between arousal scale and form features. The results revealed positive correlations between arousal and curved Z-axis angle, sum of Z-axis of curved, sloped and combination angles, 1D curvature geometry, and sum of curvature geometries (($r_s$ (18) = 0.471, $p = 0.049$), ($r_s$ (18) = 0.584, $p = 0.011$), ($r_s$ (18) = 0.657, $p = 0.003$) and ($r_s$ (18) = 0.703, $p = 0.001$), respectively). In addition, negative correlations were observed between arousal and angles towards XY-axis, sum of zero and straight Z-axis angles, full object to context scale, and sum of linear geometries (($r_s$ (18) = −0.482, $p = 0.043$), ($r_s$ (18) = −0.499, $p = 0.035$), ($r_s$ (18) = −0.562, $p = 0.015$) and ($r_s$ (18) = −0.628, $p = 0.005$), respectively).

Moreover, a Spearman's rank-order correlation for the covariation of pleasure scale and form features demonstrated positive correlations between pleasure and curved Z-axis angle, sum of Z-axis of curved, sloped, and combination angles, neutral object to object scale, and sum of curved geometries (($r_s$ (18) = 0.543, $p = 0.020$), ($r_s$ (18) = 0.683, $p = 0.002$), ($r_s$ (18) = 0.554, $p = 0.017$) and ($r_s$ (18) = 0.713, $p = 0.001$), respectively). The results further demonstrated negative correlations between pleasure and angles towards XY-axis, zero Z-axis, and sum of Z-axis of zero and straight, floor type, horizontal object to object scale, and sum of linear geometries (($r_s$ (18) = −0.618, $p = 0.006$),

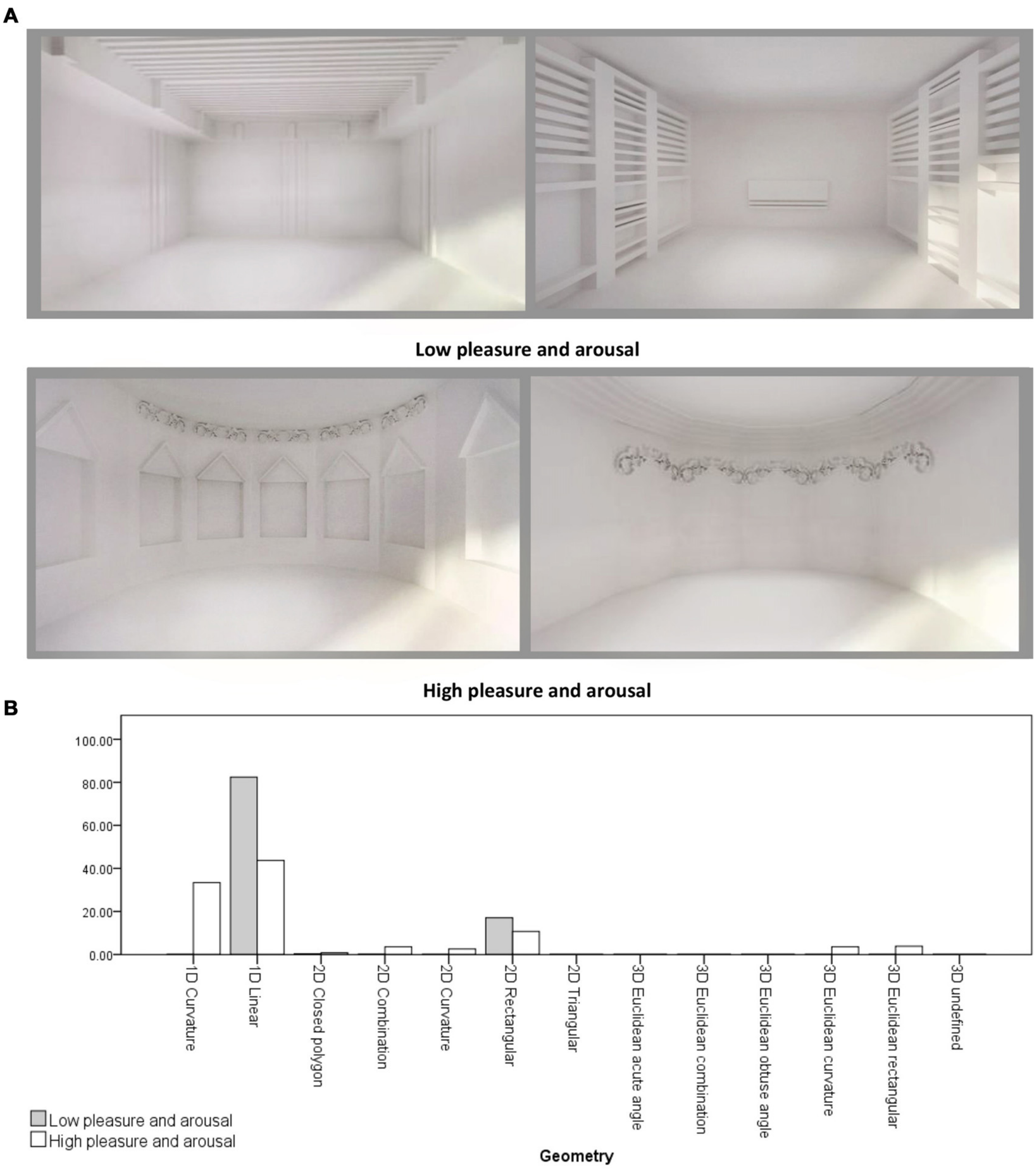


**FIGURE 4 | (A)** Samples of virtual rooms created by form features, 1st row: two rooms belong to low pleasure and arousal group, 2nd row: two rooms belong to high pleasure and arousal group. **(B)** Geometry differences between two emotion rating groups. Virtual rooms were created from Banaei et al. (2017).

($r_s$ (18) = −0.516, $p$ = 0.028), ($r_s$ (18) = −0.654, $p$ = 0.003), ($r_s$ (18) = −0.492, $p$ = 0.038), ($r_s$ (18) = −0.487, $p$ = 0.040) and ($r_s$ (18) = −0.739, $p$ = 0.0004), respectively).

## Stroop Test

Analyzing the Classic Stroop test at the end of each room trial revealed no performance differences between the formal clusters. A repeated measures ANOVA for correct to total Stroop answers (C/T) also revealed no significant differences between the formal clusters ($F_{(17,238)} = 0.944$; $p = 0.523$; $\eta^2 = 0.063$). Therefore, it can be concluded that the attention of participants was comparable for the different rooms and cannot serve as explanation for potential differences in the EEG data. The average ratio of C/T was 0.24 (σ = 0.03). We found one participant with less attention in the Stroop test (participant #8, $\bar{x} = 0.19$). We removed 16 room trials (formal clusters: cl3, cl5, cl8, cl13) in which the participant revealed a C/T below the individual standard deviation ($\bar{x}$ = 0, 0.11, 0.09, 0.11, respectively in formal clusters) of that participant from the further analysis.

## EEG Data

Repeated measures ANOVA were computed for the ERSP in using a 2 (emotion rating) × 3 (room perspective) study design. To evaluate multiple comparisons, the significance level

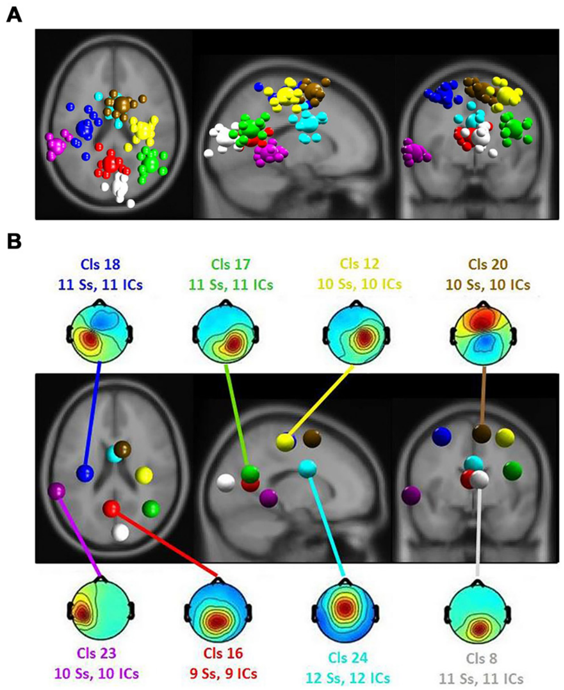


**FIGURE 5 | (A)** Equivalent-dipole locations of main clusters' independent components (ICs; small spheres) and their centroids (larger spheres), projected to the horizontal, sagittal and coronal views of the standard Montreal Neurological Institute (MNI) brain. **(B)** Clusters' centroids and their scalp maps, marked with cluster number (Cls #), number of participants (# Ss) and number of ICs (# ICs) for each cluster in the corresponding color.

($p$ value) was corrected using the FDR procedure (Benjamini and Hochberg, 1995). Only clusters with ICs of at least 60 percent of all participants were selected for analyses (see **Figure 5**).

The ERSP results revealed a significant main effect of the affective ratings ($p < 0.05$) and a main effect of the room perspective ($p < 0.05$), but no interaction effect ($p > 0.05$; see **Figure 6**). Multiple clusters demonstrated pronounced differences in several frequency bands for different room perspectives. Significant differences between the room perspectives were observed in or near the occipital lobe (Cls 8, $x = 6$, $y = -84$, $z = 17$, Brodmann area (BA) 18), in or near the precentral gyrus in both hemispheres (Cls 12, $x = 32$, $y = -20$, $z = 53$, BA 4 and Cls 18, $x = -32$, $y = -18$, $z = 54$, BA 4), the posterior cingulate cortex (Cls 16, $x = -3$, $y = -58$, $z = 16$, BA 23), the middle temporal gyrus in both hemispheres (Cls 17, $x = 40$, $y = -58$, $z = 24$, BA 39 and Cls 23, $x = -63$, $y = -40$, $z = 0$), and the superior frontal gyrus (Cls 20, $x = 9$, $y = 7$, $z = 56$, BA 6). There were significant main effects of the different room perspectives in or near the ACC (Cls 24), the left precentral gyrus (Cls 18), the posterior cingulate cortex (Cls 16) and occipital lobe (Cls 8). The ACC (Cls 24) mainly revealed theta band modulations from 3 Hz to 7 Hz in the time window up to 1200 ms after stimulus onset and in the beta band between 20 Hz–30 Hz for the time period from 700 ms to 1200 ms post stimulus. Spectral perturbations in or near the left precentral gyrus (Cls 18) revealed a significant effect in the theta band between 3 Hz and 5 Hz from stimulus onset to 500 ms post stimulus and for the frequency band from 14 to 20 Hz from 250 ms to 1200 ms post stimulus. The posterior cingulate cortex (Cls 16) demonstrated variations in the theta band around 3–5 Hz from stimulus onset to approximately 500 ms after stimulus onset with additional spectral perturbations in the frequency ranges between 9–17 Hz for the time period 300–1200 ms post stimulus. The occipital lobe (Cls 8) mainly revealed differences in theta band perturbations between 3 Hz and7 Hz for the first 500 ms and modulations of the alpha (8–13 Hz) and the beta (13–30 Hz) frequency bands from 200 ms to 1200 ms after stimulus onset. There were no further significant effects for any of the clusters in the ERSP analyses.

In addition, significant differences in specific frequency bands for the two valence groups were observed in or near the ACC (Cls 24, $x = 0$, $y = 1$, $z = 26$, BA 24). The analysis of theta activity (3–7 Hz) originating in or near the ACC (Cls 24) revealed a significant main effect for the emotional ratings with higher activity in the group with higher pleasure and arousal ratings. As **Figure 6** shows, the difference was observed mainly between 100 ms to 600 ms post stimulus onset in the frequency band 3–4 Hz.

## ERSP and Form Features Correlation

The cluster with its centroid located in or near the ACC (Cls 24) was the only cluster demonstrating differences in power modulations dependent on room perspectives as well as valence ratings. Thus, follow up analyses investigated the relationship of spectral perturbations in this cluster with architectural features as well as valence ratings. Spearman's rank-order correlations were computed to assess the relationship between ACC changes and form features. There was a positive correlation between theta power from 3 Hz to 3.5 Hz from 150 ms to 500 ms originating from the ACC and sum of Z-axis curved, sloped, and combination angles, surfaces with attachment type, 1D curvature geometry, and sum of curvature geometries (all $r_s$ (18) $\geq 0.479$, all $ps \leq 0.044$). In addition, a negative correlation between ACC theta power and pure surface type and 2D rectangular geometries was observed (all $r_s$ (18) $\leq -0.499$, all $ps \leq 0.035$). There was a positive correlation between arousal and theta power in ACC ($r_s$ (18) $= 0.720$, $p = 0.01$). The same positive covariation was observed for pleasure ratings and modulations in the theta frequency range ($r_s$ (18) $= 0.573$, $p = 0.013$).

Nonparametric partial correlation was computed to determine the relationship between form features and the ACC theta activity whilst controlling for arousal and pleasure. There was a positive significant partial correlation between surfaces with attachment type ($r_s$ (14) $= 0.525$, $p = 0.037$) and a significant negative correlation between 2D rectangular geometries and theta power in the ACC ($r_s$ (14) $= -0.579$, $p = 0.019$). The results indicate that arousal and pleasure had an influence on the relationship between theta power in the ACC and most of the form features. However, surfaces with attachment type and 2D rectangular geometries had a direct impact on theta activity in the ACC above and beyond valence and arousal.

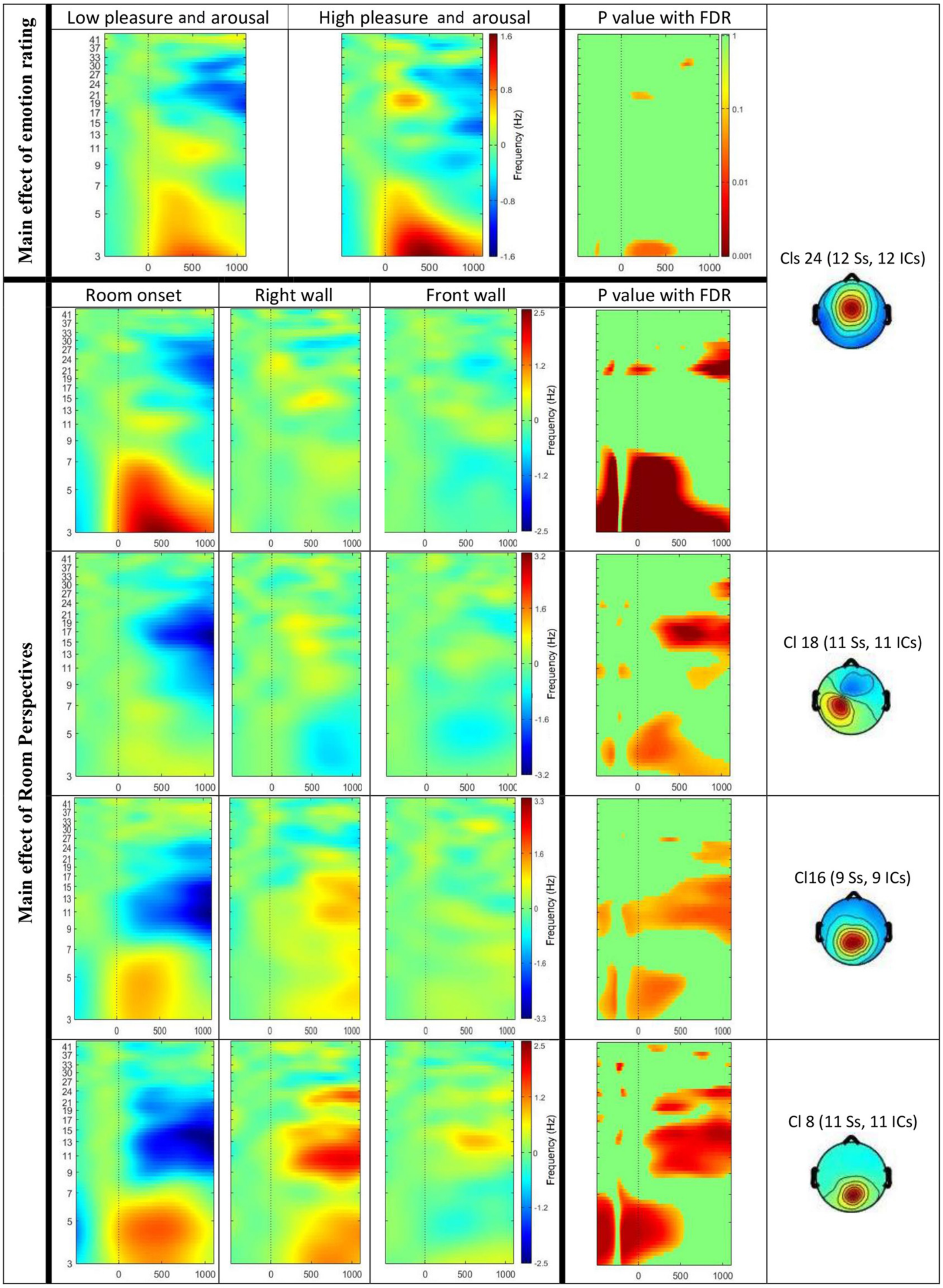


**FIGURE 6 |** Event-related spectral perturbation (ERSP) results for the main effect of visual sequences (Top) and emotion rating (Bottom). The Y-axis shows frequency (Hz) from 3 Hz to 41 Hz and the X-axis shows time (ms) from −500 ms to 1200 ms. Significant results displayed for ERSPs in or near the anterior cingulate cortex (ACC; Cls 24), the left precentral gyrus (Cls 18), the posterior cingulate cortex (Cls 16) and the occipital lobe (Cls 8). Top row displays differences in ERSP dependent on the emotional ratings for the lower pleasure and arousal group compared to the higher pleasure and arousal group. The room perspectives are displayed in the order starting with room onset, followed by onset of the right wall and the front wall. Significant differences are marked with exact *p* values with FDR correction in the most right columns.

## DISCUSSION

This study investigated human brain dynamics related to the affective impact of interior forms when the perceiver actively explores an architectural space. The study was based on a formal clustering of architectural interior forms (Banaei et al., 2017) to provide a precise description of architectural forms and to bridge the gap with previous neuroarchitectural studies. As architectural design is concerned with users' emotional experience, this study investigated the emotional experiences of different architectural forms in existing places. To allow the architectural experiences to be as realistic as possible, the participants actively moved inside the rooms, perceiving forms from different perspectives. To allow an investigation of the affective and cognitive processes and the accompanying brain dynamics during active perception of these different architectural forms, a mobile EEG setup synchronized to head-mounted VR was used.

Formal comparisons between rooms that were differently rated regarding valence and arousal revealed that rooms associated with lower pleasure and arousal ratings contained more linear geometries, while rooms with higher pleasure and arousal ratings contained more curvature geometries. The subjective measures were reflected in pronounced activity in or near the ACC for rooms that were rated higher in terms of pleasure and arousal. The formal evaluation of these rooms revealed higher densities of curvature geometries. Vartanian et al. (2013) showed similar results in an fMRI study, demonstrating higher activity in the ACC for beauty judgments of interior curvature contours. Other lines of evidence suggest a role of the ACC in emotional (Bush et al., 2000; Etkin et al., 2011), aesthetic, and artistic experiences (Kawabata and Zeki, 2004; Vartanian and Goel, 2004; Jacobsen et al., 2006; de Tommaso et al., 2008; Chatterjee, 2011). Using a mobile EEG setup synchronized to VR replicated increased ACC activity for curved features in architectural spaces. Importantly, the high temporal resolution of the EEG helped to describe the time course of the affective processing of architectural forms. This revealed a fast impact of the architectural space on activity in ACC starting around 50 ms.

Using precise form feature analysis allowed us to get deeper insights into ACC activity. Creating two groups of rooms with different features that differed in their emotional ratings, we observed significant differences in linear and curvature geometries that had an impact on theta activity generated in or near the ACC. Theta power correlated with curvature and 2D rectangular geometries, as well as the feature's type (pure surfaces and surfaces with attachment) and Z-axis angles (sum of sloped, curvature, and combination Z-axis). Both arousal ratings and ACC activity revealed correlations with form features. While angle (XY-axis) and scale (object/object and object/context) correlated with arousal scores, these features did not show any significant correlation with theta activity in the ACC. The surface type (pure and surfaces with attachment) and 2D rectangular geometries that correlated with ACC activity were not associated with arousal scores. To control for the influence of affective processes on ACC activity (Bush et al., 2000; Etkin et al., 2011; Yu et al., 2011), a partial correlation controlling for arousal and pleasure ratings was computed. The results showed an impact of surfaces with attachment type and 2D rectangular geometries beyond the emotional impact of these features. Such surfaces with attachment could be walls, ceilings, or floors having additional feature(s) like a linear solid or a 3D solid attached to it. This finding indicated that the significant changes in ACC theta band activity was not only because of the effect of arousal or valence of the form features, but also because of the processing aspects of architectural features in the built environment.

Several studies revealed that affective responses to environments are automatic and unconscious (Ulrich, 1983, p. 91; Korpela et al., 2002; Valtchanov and Ellard, 2015; Coburn et al., 2017). This rapidly occurring effect beyond the conscious reflection of affective processes cannot be described without neuroscientific methods with high temporal resolution. While EEG showed the instantaneous effect of forms on brain dynamics while moving through architectural spaces, the SAM test allowed assessing the emotional impact after perceiving different perspectives of the rooms. Different covariations between electrophysiological activity and subjective ratings might thus be attributed to the delay in the subjective test at the end of a trial where the complete room was experienced for an extended period of time.

The ACC is involved in motor control, cognition and arousal (Paus, 2001). Aesthetic experiences, which represent a mixture of these processes, arise from neural systems underlying the sensory–motor, emotion–valuation and meaning–knowledge interactions (Chatterjee and Vartanian, 2014). The present study demonstrated comparable changes in theta activity originating in or near the ACC for two groups with different emotion ratings (containing movement, cognition, and arousal) and perception of different room perspectives (containing movement and cognition). These results further support the central role of ACC in aesthetic and architectural experiences. Because we inhabit and move in architectural space, our responses to architecture can be different from our responses to art (Pallasmaa, 2005, p. 63; Coburn et al., 2017). The aesthetic experience of both architecture and art, however, is reflected in the ACC activity. One possible functional explanation of the fast theta response originating in ACC might be the affordance of an architectural space that can be actively explored. As per the aesthetic triad of Chatterjee and Vartanian (2014), sensory-motor perception of rectilinear and curvature geometries can influence this aesthetic experience as well as differences in the perceived emotion and meaning. Along the same lines, Pallasmaa (2005) suggested the interaction between the sensory-motor and meaning (memory) to perceive architecture. He emphasized that architecture is not a series of images, nor are visual units and gestalt. Architecture is a kind of experience that interact with meaning (memory) and body movement (Pallasmaa, 2005, p. 63). During natural strolling, curves represent continuous forms and have similar views from different perspectives, while rectilinear geometries have focal points and provide different views from different perspectives.

The experience of different room perspectives was associated with differences in the density of form features and the time that the participants perceived these features while moving through the architectural space. The first impression with the onset of the room entrance gave a view of the ceiling, the floor and the walls of the space. After the onset of these stimuli, participants walked or turned and perceived different perspectives. Consequently, experiencing the right and front walls was based on fewer form features and only a limited view of the specifics of the room walls. The view into the complete space and the views toward specific walls had different perspectives. Additionally, while both room onset and front wall perspectives included the front wall, they differed in terms of the perceived depth of the space. Different room perspectives were accompanied by differences in ACC activity, implying a strong impact of the first impression of a room. This impression faded with the passing of time in the same architectural space, leading to repeated and comparable visual input. The significant impact of the first impression was reflected in the early onset of theta power increases of about 500 ms after the stimulus onset. Also within this time period, the differences in architectural features became apparent, as demonstrated in the significant differences in ACC theta modulations in curvature geometric forms.

While ACC activity showed a clear association with affective ratings and form features, other brain areas also demonstrated task-related activity. As expected, motor areas revealed significant differences in spectral perturbations between different perspectives of the rooms. This result revealed different activation patterns depending on the movement through space to get a different perspective for the same room. Spectral perturbations in motor areas in both the right and the left hemispheres were comparable for movement through architectural spaces. This result supports the assumption that exploration and the accompanying brain dynamics did not differ between different architectural interiors above and beyond active movement. Posterior areas of the brain (posterior cingulate cortex and occipital lobe) showed higher activity in the beta band when participants experienced the right wall, potentially reflecting changes in perspective during movement in space. The posterior cingulate cortex revealed significant differences between perspectives (room onset and right wall) and depth changes (room onset and front wall). While there is some evidence regarding the involvement of the PCC in emotional processes (Maddock, 1999; Maddock et al., 2003), the changes in PCC more likely reflect heading changes during movement in space (Gramann et al., 2010b; Chiu et al., 2012; Lin et al., 2015). There seems to be a fundamental contrast between the functions of the anterior and the posterior aspect of the cingulate cortex, suggesting an involvement of the anterior part in emotional control and the posterior in spatial orientation (Vogt et al., 1992). Our results support this assumption, thereby revealing effects of heading changes in the posterior cingulate cortex but no effects of emotional ratings. In line with this argument, the occipital lobe demonstrated an activity pattern that reflected changes in perspective and perceived room depths. This is in line with the primary and secondary visual cortices in the perception of perspective (Welchman et al., 2005). Mainly neurons in the visual cortex are sensitive to shapes and the orientation of lines during motion (Mallgrave, 2010, p. 142) possibly reflected in beta band activity. Emotional ratings revealed no impact on activity in the occipital lobe. The absence of significant activation differences in the precuneus, as reported by Vartanian et al. (2015), might be explained by the differences in the architectural spaces in the two studies. While high ceilings activated the visuospatial area in the left precuneus in the study of Vartanian et al. (2015), the present study controlled room heights.

## Limitations

While this study is novel with respect to the methods used, some limitations should be considered. One of the important issues for designing this study was the time a perceiver spent in a room to explore different interior aspects and to develop an affective response to the same. Sufficient time is needed to extract emotional experiences to the stimuli (Bekhtereva and Müller, 2015). However, the longer participants spent in one room, the fewer the room trials that can be collected, leading to non-optimal signal-to-noise ratios for EEG analyses. This study was intended to achieve a reasonable number of trials for EEG analyses while presenting a variety of architectural spaces that were formally described using a quantitative measure to derive formal clusters of the feature space. Future studies should increase the number of room trials by focusing on selected clusters as described in this study.

# CONCLUSION

To sum up, the results of the present study indicate that natural movement through the built environment leads to rapid responses in the ACC that reflect a first affective response to the architectural features of the environment. Curvature forms lead to stronger theta synchronization in the ACC and are correlated with higher positive ratings regarding the affective state of the participants. Moreover, partial correlations with the density of 2D rectangular geometries and the type of surfaces clearly indicated an involvement of the ACC in processing architectural features beyond their emotional impact. While the posterior cingulate cortex and the occipital lobe were involved in the perception of different perspectives and changes in room depths, there was no significant difference for the rather small perceptual changes in perspective between different walls of the same architectural space. This indicates a strong initial impression of the environment on the affective and perceptual aspects of the space with a fast decline in the impact of architectural features on affective and perceptual processes.

The present study extends existing research by controlling the presentation using a quantitative approach in order to analyze architectural features, and by allowing the perceiver to walk through the architectural space to gain different perspectives of the same room. The results demonstrate that interior form is defined not only by the geometry and by the features such as type, location, scale, and angle, but also by the way the inhabitant experiences this environment. This study also sheds a new light on the role of the ACC in the natural experience of architectural spaces. Natural movement is the best way to investigate the brain dynamics underlying natural perception and affective processes associated with perceiving a 3D environment. The insights gained from this kind of MoBI approach using fine-grained analyses of architectural forms and natural movement within virtual spaces while recording EEG activity provide fresh insights into neuroarchitecture. This interdisciplinary study showed the possibility of using MoBI and VR to systematically develop architectural studies.

## AUTHOR CONTRIBUTIONS

MB conceptualized the research. KG and MB developed the experimental design and wrote the manuscript. JH was involved in experimental design. MB created the 3D models and the VR environment. MB recruited experimental participants, acquired and analyzed the data. KG supervised and participated in the data analysis. JH, AY and KG supervised the research.

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## REFERENCES

Ackerman, J. S., Collins, P., and Gowans, A. (2017). *Architecture (Form) Encyclopædia Britannica.* Edinburgh: Encyclopædia Britannica, Inc.

Banaei, M., Ahmadi, A., and Yazdanfar, A. (2017). Application of AI methods in clustering of architecture interior forms. *Front. Arch. Res.* 6, 360–373. doi: 10.1016/j.foar.2017.05.002

Banaei, M., Yazdanfar, A., Nooreddin, M., and Yoonessi, A. (2015). Enhancing urban trails design quality by using electroencephalography Device. *Procedia Soc. Behav. Sci.* 201, 386–396. doi: 10.1016/j.sbspro.2015.08.191

Bar, M., and Neta, M. (2006). Humans prefer curved visual objects. *Psychol. Sci.* 17, 645–648. doi: 10.1111/j.1467-9280.2006.01759.x

Bar, M., and Neta, M. (2007). Visual elements of subjective preference modulate amygdala activation. *Neuropsychologia* 45, 2191–2200. doi: 10.1016/j.neuropsychologia.2007.03.008

Bekhtereva, V., and Müller, M. M. (2015). Affective facilitation of early visual cortex during rapid picture presentation at 6 and 15 Hz. *Soc. Cogn. Affect. Neurosci.* 10, 1623–1633. doi: 10.1093/scan/nsv058

Benjamini, Y., and Hochberg, Y. (1995). Controlling the false discovery rate: a practical and powerful approach to multiple testing. *J. R. Stat. Soc. Series B Methodol.* 57, 289–300. doi: 10.1214/15-aos1337supp

Bradley, M. M., and Lang, P. J. (1994). Measuring emotion: the self-assessment manikin and the semantic differential. *J. Behav. Ther. Exp. Psychiatry* 25, 49–59. doi: 10.1016/0005-7916(94)90063-9

Bush, G., Luu, P., and Posner, M. I. (2000). Cognitive and emotional influences in anterior cingulate cortex. *Trends Cogn. Sci.* 4, 215–222. doi: 10.1016/s1364-6613(00)01483-2

Chatterjee, A. (2011). Neuroaesthetics: a coming of age story. *J. Cogn. Neurosci.* 23, 53–62. doi: 10.1162/jocn.2010.21457

Chatterjee, A., and Vartanian, O. (2014). Neuroaesthetics. *Trends Cogn. Sci.* 18, 370–375. doi: 10.1016/j.tics.2014.03.003

Chiu, T. C., Gramann, K., Ko, L. W., Duann, J. R., Jung, T. P., and Lin, C. T. (2012). Alpha modulation in parietal and retrosplenial cortex correlates with navigation performance. *Psychophysiology* 49, 43–55. doi: 10.1111/j.1469-8986.2011.01270.x

Choo, H., Nasar, J. L., Nikrahei, B., and Walther, D. B. (2017). Neural codes of seeing architectural styles. *Sci. Rep.* 7:40201. doi: 10.1038/srep40201

Cichy, R. M., Chen, Y., and Haynes, J.-D. (2011). Encoding the identity and location of objects in human LOC. *Neuroimage* 54, 2297–2307. doi: 10.1016/j.neuroimage.2010.09.044

Coburn, A., Vartanian, O., and Chatterjee, A. (2017). Buildings, beauty, and the brain: a neuroscience of architectural experience. *J. Cogn. Neurosci.* 29, 1521–1531. doi: 10.1162/jocn_a_01146

Dazkir, S. S. (2009). *Emotional Effect of Curvilinear Vs. Rectilinear forms of Furniture in Interior Settings.* Oregon, OR: Master's Thesis, Oregon State University.

Delorme, A., and Makeig, S. (2004). EEGLAB: an open source toolbox for analysis of single-trial EEG dynamics including independent component analysis. *J. Neurosci. Methods* 134, 9–21. doi: 10.1016/j.jneumeth.2003.10.009

de Tommaso, M., Sardaro, M., and Livrea, P. (2008). Aesthetic value of paintings affects pain thresholds. *Conscious. Cogn.* 17, 1152–1162. doi: 10.1016/j.concog.2008.07.002

Eagleman, D. (2015). *The Brain: The Story of You.* New York, NY: Pantheon.

Edelstein, E. A. (2008). Building health. *HERD* 1, 54–59. doi: 10.1177/193758670800100208

Edelstein, E. A., and Macagno, E. (2012). "Form follows function: bridging neuroscience and architecture," in *Sustainable Environmental Design in Architecture: Impacts on Health*, eds S. T. Rassia and P. M. Pardalos (New York, NY: Springer), 27–42.

Etkin, A., Egner, T., and Kalisch, R. (2011). Emotional processing in anterior cingulate and medial prefrontal cortex. *Trends Cogn. Sci.* 15, 85–93. doi: 10.1016/j.tics.2010.11.004

Ghoshal, T., Boatwright, P., and Malika, M. (2016). *The Psychology of Design.* Abingdon: Routledge.

Gramann, K. (2013). Embodiment of spatial reference frames and individual differences in reference frame proclivity. *Spat. Cogn. Comput.* 13, 1–25. doi: 10.1080/13875868.2011.589038

Gramann, K., Ferris, D. P., Gwin, J., and Makeig, S. (2014). Imaging natural cognition in action. *Int. J. Psychophysiol.* 91, 22–29. doi: 10.1016/j.ijpsycho.2013.09.003

Gramann, K., Gwin, J. T., Bigdely-Shamlo, N., Ferris, D. P., and Makeig, S. (2010a). Visual evoked responses during standing and walking. *Front. Hum. Neurosci.* 4:202. doi: 10.3389/fnhum.2010.00202

Gramann, K., Onton, J., Riccobon, D., Mueller, H. J., Bardins, S., and Makeig, S. (2010b). Human brain dynamics accompanying use of egocentric and allocentric reference frames during navigation. *J. Cogn. Neurosci.* 22, 2836–2849. doi: 10.1162/jocn.2009.21369

Gramann, K., Gwin, J. T., Ferris, D. P., Oie, K., Jung, T.-P., Lin, C.-T., et al. (2011). Cognition in action: imaging brain/body dynamics in mobile humans. *Rev. Neurosci.* 22, 593–608. doi: 10.1515/RNS.2011.047

Gwin, J. T. (2012). *Noninvasive Electrical Neuroimaging of the Human Brain During Mobile Tasks Including Walking and Running*. Ann Arbor, MI: Doctoral Dissertation, University of Michigan.

Gwin, J. T., Gramann, K., Makeig, S., and Ferris, D. P. (2010). Removal of movement artifact from high-density EEG recorded during walking and running. *J. Neurophysiol.* 103, 3526–3534. doi: 10.1152/jn.00105.2010

Hevner, K. (1935). Experimental studies of the affective value of colors and lines. *J. Appl. Psychol.* 19, 385–398. doi: 10.1037/h0055538

Jacobsen, T., Schubotz, R. I., Höfel, L., and Cramon, D. Y. V. (2006). Brain correlates of aesthetic judgment of beauty. *Neuroimage* 29, 276–285. doi: 10.1016/j.neuroimage.2005.07.010

Jungnickel, E., and Gramann, K. (2016). Mobile Brain/Body Imaging (MoBI) of physical interaction with dynamically moving objects. *Front. Hum. Neurosci.* 10:306. doi: 10.3389/fnhum.2016.00306

Kawabata, H., and Zeki, S. (2004). Neural correlates of beauty. *J. Neurophysiol.* 91, 1699–1705. doi: 10.1152/jn.00696.2003

Kirk, U., Skov, M., Christensen, M. S., and Nygaard, N. (2009). Brain correlates of aesthetic expertise: a parametric fMRI study. *Brain Cogn.* 69, 306–315. doi: 10.1016/j.bandc.2008.08.004

Korpela, K. M., Klemettilä, T., and Hietanen, J. K. (2002). Evidence for rapid affective evaluation of environmental scenes. *Environ. Behav.* 34, 634–650. doi: 10.1177/0013916502034005004

Kothe, C. (2014). Lab Streaming Layer (LSL). Available online at: https://github.com/sccn/labstreaminglayer

Küller, R., Mikellides, B., and Janssens, J. (2009). Color, arousal, and performance—A comparison of three experiments. *Color Res. Appl.* 34, 141–152. doi: 10.1002/col.20476

Lancaster, J. L., Woldorff, M. G., Parsons, L. M., Liotti, M., Freitas, C. S., Rainey, L., et al. (2000). Automated Talairach atlas labels for functional brain mapping. *Hum. Brain Mapp.* 10, 120–131. doi: 10.1002/1097-0193(200007)10:3<120::aid-hbm30>3.0.co;2-8

Lin, C.-T., Chiu, T.-C., and Gramann, K. (2015). EEG correlates of spatial orientation in the human retrosplenial complex. *Neuroimage* 120, 123–132. doi: 10.1016/j.neuroimage.2015.07.009

Lundholm, H. (1921). The affective tone of lines: experimental researches. *Psychol. Rev.* 28, 43–60. doi: 10.1037/h0072647

Madani Nejad, K. (2007). *Curvilinearity in Architecture: Emotional Effect of Curvilinear forms in Interior Design.* Texas, TX: Doctoral Dissertation, Texas A&M University. Available online at: http://hdl.handle.net/1969.1/5750

Maddock, R. J. (1999). The retrosplenial cortex and emotion: new insights from functional neuroimaging of the human brain. *Trends Neurosci.* 22, 310–316. doi: 10.1016/s0166-2236(98)01374-5

Maddock, R. J., Garrett, A. S., and Buonocore, M. H. (2003). Posterior cingulate cortex activation by emotional words: fMRI evidence from a valence decision task. *Hum. Brain Mapp.* 18, 30–41. doi: 10.1002/hbm.10075

Makeig, S., Gramann, K., Jung, T.-P., Sejnowski, T. J., and Poizner, H. (2009). Linking brain, mind and behavior. *Int. J. Psychophysiol.* 73, 95–100. doi: 10.1016/j.ijpsycho.2008.11.008

Mallgrave, H. F. (2010). *The Architect's Brain: Neuroscience, Creativity and Architecture.* Hoboken, NJ: Wiley-Blackwell, John Wiley & Sons, Ltd.

Mehrabian, A., and Russell, J. A. (1974). *An Approach to Environmental Psychology.* Cambridge, MA: The MIT Press.

Nanda, U., Pati, D., Ghamari, H., and Bajema, R. (2013). Lessons from neuroscience: form follows function, emotions follow form. *Intell. Build. Int.* 5, 61–78. doi: 10.1080/17508975.2013.807767

Nasr, S., Echavarria, C. E., and Tootell, R. B. H. (2014). Thinking outside the box: rectilinear shapes selectively activate scene-selective cortex. *J. Neurosci.* 34, 6721–6735. doi: 10.1523/JNEUROSCI.4802-13.2014

OED (Ed.). (2016). *Oxford English Dictionary.* Oxford: Oxford University Press.

Oostenveld, R., and Oostendorp, T. F. (2002). Validating the boundary element method for forward and inverse EEG computations in the presence of a hole in the skull. *Hum. Brain Mapp.* 17, 179–192. doi: 10.1002/hbm.10061

Oostenveld, R., and Praamstra, P. (2001). The five percent electrode system for high-resolution EEG and ERP measurements. *Clin. Neurophysiol.* 112, 713–719. doi: 10.1016/s1388-2457(00)00527-7

Pallasmaa, J. (2005). *The Eyes of the Skin: Architecture and the Senses.* Hoboken, NJ: Great Britain, Wiley-Academy, John Wiley & Sons Ltd.

Paus, T. (2001). Primate anterior cingulate cortex: where motor control, drive and cognition interface. *Nat. Rev. Neurosci.* 2, 417–424. doi: 10.1038/35077500

Poffenberger, A. T., and Barrows, B. E. (1924). The feeling value of lines. *J. Appl. Psychol.* 8, 187–205. doi: 10.1037/h0073513

Robinson, S., and Pallasmaa, J. (2015). *Mind in Architecture: Neuroscience, Embodiment, and the Future of Design.* Cambridge, MA: MIT Press.

Roe, J. J., Aspinall, P. A., Mavros, P., and Coyne, R. (2013). Engaging the brain: the impact of natural versus urban scenes using novel EEG methods in an experimental setting. *Environ. Sci.* 1, 93–104. doi: 10.12988/es.2013.3109

Roelfsema, P. R., Scholte, H. S., and Spekreijse, H. (1999). Temporal constraints on the grouping of contour segments into spatially extended objects. *Vision Res.* 39, 1509–1529. doi: 10.1016/s0042-6989(98)00222-3

Shemesh, A., Talmon, R., Karp, O., Amir, I., Bar, M., and Grobman, Y. J. (2017). Affective response to architecture-investigating human reaction to spaces with different geometry. *Archit. Sci. Rev.* 60, 116–125. doi: 10.1080/00038628.2016.1266597

Shin, Y.-B., Woo, S.-H., Kim, D.-H., Kim, J., Kim, J.-J., and Park, J. Y. (2014). The effect on emotions and brain activity by the direct/indirect lighting in the residential environment. *Neurosci. Lett.* 584, 28–32. doi: 10.1016/j.neulet.2014.09.046

Sternberg, E. M. (2010). *Healing Spaces: the Science of Place and Well-being.* Cambridge, MA: Harvard University Press.

Stroop, J. R. (1935). Studies of interference in serial verbal reactions. *J. Exp. Psychol.* 18, 643–662. doi: 10.1037/h0054651

Tsunetsugu, Y., Miyazaki, Y., and Sato, H. (2005). Visual effects of interior design in actual-size living rooms on physiological responses. *Build. Environ.* 40, 1341–1346. doi: 10.1016/j.buildenv.2004.11.026

Ulrich, R. S. (1983). "Aesthetic and affective response to natural environment," in *Behavior and the Natural Environment*, eds I. Altman and J. F. Wohlwill (New York, NY: Plenum Press), 85–125.

Valtchanov, D., and Ellard, C. G. (2015). Cognitive and affective responses to natural scenes: effects of low level visual properties on preference, cognitive load and eye-movements. *J. Environ. Psychol.* 43, 184–195. doi: 10.1016/j.jenvp.2015.07.001

Vartanian, O., and Goel, V. (2004). Neuroanatomical correlates of aesthetic preference for paintings. *Neuroreport* 15, 893–897. doi: 10.1097/00001756-200404090-00032

Vartanian, O., Navarrete, G., Chatterjee, A., Fich, L. B., Gonzalez-Mora, J. L., Leder, H., et al. (2015). Architectural design and the brain: effects of ceiling height and perceived enclosure on beauty judgments and approach-avoidance decisions. *J. Environ. Psychol.* 41, 10–18. doi: 10.1016/j.jenvp.2014.11.006

Vartanian, O., Navarrete, G., Chatterjee, A., Fich, L. B., Leder, H., Modroño, C., et al. (2013). Impact of contour on aesthetic judgments and approach-avoidance decisions in architecture. *Proc. Natl. Acad. Sci. U S A* 110, 10446–10453. doi: 10.1073/pnas.1301227110

Vecchiato, G., Tieri, G., Jelic, A., De Matteis, F., Maglione, A. G., and Babiloni, F. (2015). Electroencephalographic correlates of sensorimotor integration and embodiment during the appreciation of virtual architectural environments. *Front. Psychol.* 6:1944. doi: 10.3389/fpsyg.2015.01944

Vogt, B. A., Finch, D. M., and Olson, C. R. (1992). Functional heterogeneity in cingulate cortex: the anterior executive and posterior evaluative regions. *Cereb. Cortex* 2, 435–443. doi: 10.1093/cercor/2.6.435-a

Welchman, A. E., Deubelius, A., Conrad, V., Bülthoff, H. H., and Kourtzi, Z. (2005). 3D shape perception from combined depth cues in human visual cortex. *Nat. Neurosci.* 8, 820–827. doi: 10.1038/nn1461

Yu, C., Zhou, Y., Liu, Y., Jiang, T., Dong, H., Zhang, Y., et al. (2011). Functional segregation of the human cingulate cortex is confirmed by functional connectivity based neuroanatomical parcellation. *Neuroimage* 54, 2571–2581. doi: 10.1016/j.neuroimage.2010.11.018

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# Quantifying Human Experience in Architectural Spaces with Integrated Virtual Reality and Body Sensor Networks

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**Abstract:** People spend more than 90% of their time indoors, making it essential to understand how the built environment can influence human experience and assess how the changes in architectural design features can impact this experience. Human experience in an architectural space is defined as the state of mind that is reflected on our physiological, emotional, and cognitive statuses. Previous studies attempted to explain the relation between architectural design features (e.g., the existence of daylight and connectivity to nature) and human experience. However, the extent of how different design features influence human experience has not been fully quantified yet. This study provides an integrated method that fuses virtual reality and noninvasive body area sensor networks (BSNs) to quantify human experience in architectural spaces. Using a set of biometric sensors, several physiological metrics such as skin conductance, brain activity, and heart rate were captured and examined while subjects were navigating and performing tasks in virtual environments (VEs). The integrated platform has been used to quantify the sense of stress and anxiety through structured user experiments in a visualization laboratory using alternate VEs configured by varying the related set of architectural design features. To generalize the findings of this study, a large pool of participants was invited to the experiments, where statistically significantly different results could be obtained. The analysis of the collected body sensor data showed that the human response changes with architectural design, with more than 40% of the electroencephalogram (EEG) oscillations having higher values across all channels on all frequency bands, 141% having an increase in galvanic skin response (GSR) readings, and lower heart rate variability in photoplethysmogram (PPG) in the stress-reducing environment as compared with the stress-inducing environment. The presented approach provides a systematic way for architectural design firms to get user feedback before the design is finalized for achieving the ultimate experience among the proposed design alternatives. **DOI: 10.1061/(ASCE)CP.1943-5487.0000812.** 

**Author keywords:** Virtual reality; Body sensor networks; Biometric sensors; Electroencephalogram (EEG); Architecture design; Human experience; Neuroscience.



## Introduction

The impact of the built environment on the human experience and performance has long been argued in the architectural and neuroscience research. Moreover, the interrelations between human responsiveness and the built environment, and the degree to which the design of our built environment can contribute to increased performance and satisfaction of our needs (e.g., healing environment or better learning experience) are not fully understood yet. This understanding is essential as we spend more and more time indoors, currently more than 90% of our time (Höppe 2002).

Human experience in the built environment refers to the human state of mind that is affected by the surrounding environments and reflected on our psychological, physiological, and emotional measures. This experience is particularly reflected on the cognitive and physical state of the human body (Eberhard 2009; Western et al. 1981). One of the main challenges in quantifying the impact of architectural design features on human experience is to create controlled testing environments (Franz et al. 2005) in which individual architectural design features can be altered and tested individually. So far, this has been practically infeasible and costly. However, recent technological advancements, such as building information modeling (BIM) and virtual reality (VR), provide opportunities to overcome this limitation by offering the flexibility to rapidly replicate and alter real environments under controlled conditions with a high degree of realism for users (Zou et al. 2017; Du et al. 2017; Heydarian et al. 2015; Saeidi et al. 2017).

Another challenge to the empirical research is the lack of effective methods used to quantify the impacts of configured architectural design features on human experience. Traditional methods of assessing human experience in a space include self-reports and focus groups with occupants to ask about their perception and satisfaction with their built environment. Those are subjective methods that limit researchers to learning about such experience from the self-reporting of subjects. Objective means and methods of measurements are required to understand how changes in architectural forms impact human experience. Advancements in the wearable sensing technology provide opportunities to capture unbiased data on human physiological, emotional, and cognitive states that can be correlated with human experience.

The research presented in this paper aims to quantify the impact of architectural design features on human experience using an integrated platform of VR and a body sensor network (BSN) with the

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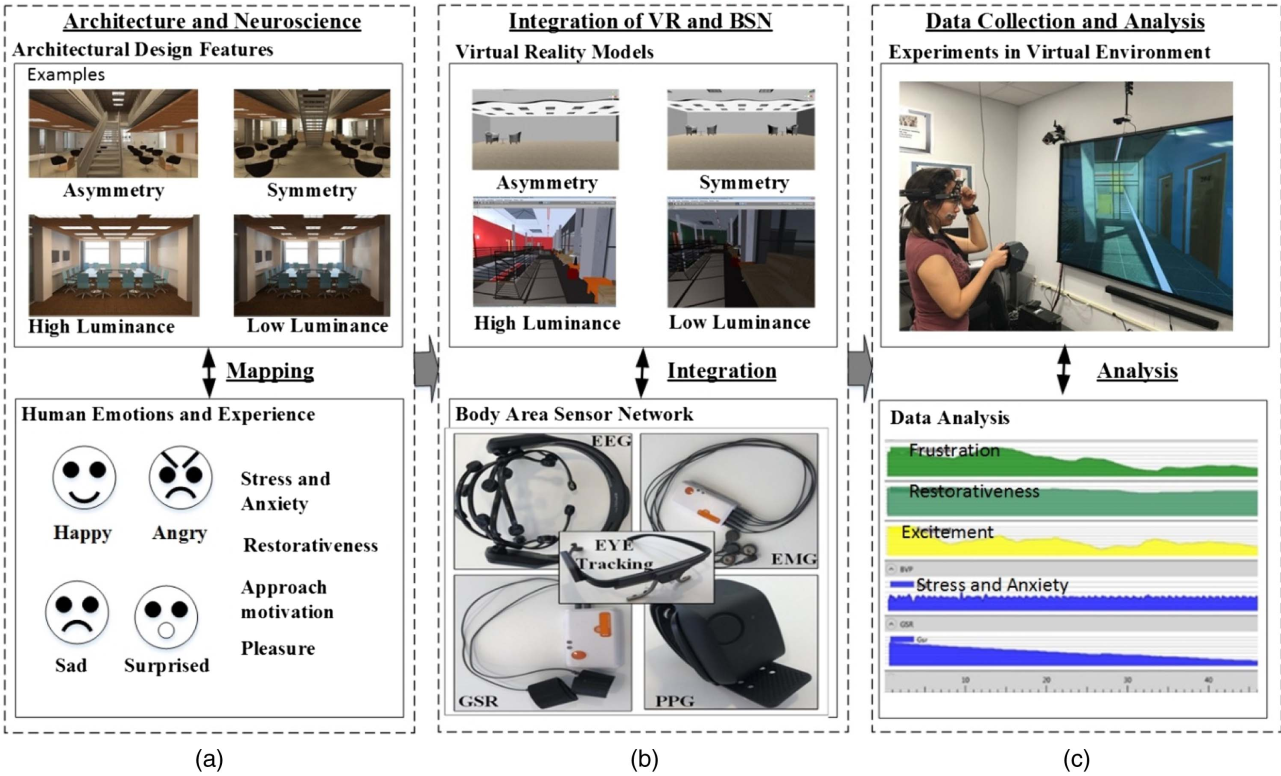


**Fig. 1.** Overview of the research vision and approach: (a) mapping of architectural design features and human experience; (b) integration of virtual reality and body area sensor network; and (c) user studies to collect body area sensor network data and data analysis.

objective to improve the current design practice with features that highly correlate with positive experience. Those interactions are important to understand both for people who utilize buildings on a daily basis, and for architects, who design facilities that aim to provide positive experiences in space usage. This paper introduces the integrated platform to measure human bodily responses in configured virtual spaces for various human experiences. This paper also provides the results of user studies performed in a visualization laboratory on the quantified impact of architectural design features on stress and anxiety as the human experience being analyzed.

## Vision

The vision is to integrate VR and biometric sensors, and conduct user studies to measure the human bodily responses in virtual environments (VEs) designed with architectural design features to give various experiences to users (Fig. 1). Architectural design features are defined as the elements that form a space with which people interact and give the space its unique characteristics (van Leeuwen and Wagter 1997). Those features are believed to impact one's experience in a space from feeling comfortable to inspired and from being stressed to distracted (Franz et al. 2005). Examples of those features include the level of luminance, windows size, presence of natural elements in the space, and various others. Detailed discussions on these features are provided in "Literature Review."

This vision integrates the domains of architecture, neuroscience, and environmental psychology. Investigation in the architecture domain provides the architectural design features that architects use in their designs to give different experiences (e.g., relaxing, restorative, motivational) to users [Fig. 1(a)]. Environmental psychology defines experiences that we sense in specific environments, and the neuroscience domain provides the means and methods to measure such experiences. Given these as inputs, the approach integrates a set of biometric tools such as the electroencephalogram (EEG) to measure the electrical activity of the human brain, the galvanic skin response (GSR) to measure the electrical conductance of the skin (also known as the galvanic skin response), the facial- or vision-based electromyography (EMG) to measure the facial expressions, eye tracking to measure the eye movements of people in spaces, and the photoplethysmogram (PPG) to measure heart rate changes [Fig. 1(b)]. These sensors are utilized along with VEs designed for triggering different types of human experience and results are analyzed and compared to quantify the impact of architectural design features provided in VEs on humans.

The integrated platform is utilized for user tests in a visualization laboratory with motion tracking solutions [Fig. 1(c)]. The platform is such that during a user test, each user completes tasks in multiple VEs (as detailed subsequently in the paper). As they perform these tasks in the VEs, their biometric data are captured along with the actions taken during the experiment. The approach also integrates subjective measures, which include self-reports of users on how they feel while interacting with the VEs. Finally, resulting sensor data captured throughout experiments in VEs are analyzed along with self-reports of users using statistical methods for the quantification of design on human experience. The scope of this paper is set on the human experience related to stress and anxiety in architectural spaces and the biometric sensor data captured and analyzed for the reported experiments include EEG, GSR, and PPG only.

## Literature Review

The research presented in this paper builds on the research studies that investigated the (a) methods used in the architecture domain to understand the impact of architecture design on human experience, (b) architectural design features and their influence on stress and anxiety as a human experience, and (c) the current methods in the neuroscience domain used to evaluate human physiological and psychological states.

### Methods Used to Evaluate Human Physiological and Psychological Responses

The current practice of architectural performance evaluations involves utilizing tools such as evidence-based design (EBD), in which practitioners closely look for evidence from occupants that could improve the quality of life of occupants and use them for justifying future design decisions (Pati 2011). EBD is mainly practiced for the design of health care facilities, where approaches are implemented to identify credible evidence that positively influence patient well-being, safety, and healing. EBD utilizes postoccupancy evaluations (POEs), which refer to the systematical evaluation of the effectiveness of various aspects of the design including functionality, productivity, aesthetics, and sustainability (Sanoff 2001). The means and methods used for postoccupancy evaluations include questionnaires, one-to-one interviews, field observations, walkthroughs, focus groups, photographic surveys, recordings of the use of time, and looking at the physical evidence of use (Turpin-Brooks and Viccars 2006). Those methods are not well suited for objectively quantifying the impact of architectural design features on human experience.

Research studies at the intersection of the neuroscience and architecture domains focused on specific design characteristics such as wayfinding options (Edelstein et al. 2008), connectivity of pathways (Dara-Abrams 2014), and aesthetics of urban layouts (Skorupka 2008) and evaluated the results of user studies captured through different modalities (e.g., VEs, paper and pencil, maps). While it is ideal to configure actual designed spaces to have various design features for the user experiments, it is not feasible to reconfigure changes (e.g., size of windows) in realistic settings, hence the experiments were conducted only in virtual, but controlled, settings. Regarding the use of virtual environments, the technology has been utilized in studies for examining evacuation (e.g., Zou et al. 2017; Andrée et al. 2016; Duarte et al. 2014), human visual perception and energy behavior (e.g., Chokwitthaya et al. 2017; Saeidi et al. 2017), and human experience in architectural spaces (e.g., Radwan and Ergan 2017; Edelstein et al. 2008). Instead of evaluating the overall human experience in a space that is composed of various architectural design features, what was common in these studies was that they either focused on certain characteristics such as daylighting and space isolation on humans (Franz et al. 2005; Yildirim et al. 2007) or utilized self-reports or a single biometric sensor to relate design characteristics to human experience. Although it has been widely used in previous research (Geiser and Walla 2011), self-reports are limited due to their subjectivity. Hence, at the intersection of neuroscience and architecture, there is still a lack of empirical evidence on the way a collective set of architectural design features impacts human experience.

### Architectural Design Features and Their Influence on Stress and Anxiety

Architectural design features impact our experience in a space in a wide range and each design feature has an influence on specific human experience (Eberhard 2009). This research focused on the architectural design features that are studied and mentioned in the literature in relation to stress and anxiety. Researchers analyzed the relationship between the design of indoor environments and stress levels especially in health care, schools, and office buildings (Beukeboom et al. 2012; Parsons et al. 1998; Rashid and Zimring 2008; Ulrich et al. 2008). Findings showed that in many cases, certain configurations of indoor environments may set forth a process leading to stress by affecting individual and/or workplace needs. As summarized in Table 1, these configurations typically have variations in availability of natural view, luminance levels, colors, and the presence or absence of visual or wayfinding cues and landmarks that either reduce stress or increase it (Devlin and Arneill 2003; Edelstein et al. 2008; Heschong 2003a, b; Hidayetoglu et al. 2012; Rashid and Zimring 2008; Skorupka 2008; Ulrich 1984; Ulrich et al. 2008). While it is ideal to configure actual designed spaces to have various design features for the user experiments, it is extremely unlikely to happen in the real world, where the design is nearly impossible to change once construction is complete. For example, researchers concluded that lighting and level of luminance influence our stress and anxiety levels, where darker spaces have a negative impact on stress levels during exposure to cognitive loads (e.g., Farbstein and Farling 2006; Sternberg and Wilson 2006).

Based on the point of departure information given in Table 1, the study to evaluate the integrated VR + BSN platform focused on the assessment of the architectural designed features that are linked to triggering stress and anxiety, which are level of luminance, presence or absence of visual cues (e.g., interior or exterior landmarks,

**Table 1.** Summary of previous work on architectural design features affecting stress levels

| Architectural design features | Feature impacts stress levels | Linkage between positive or negative experience on stress |
|---|---|---|
| Level of luminance literature consensus: dark luminance increases stress | Rashid and Zimring (2008), Butterworth (2000), Devlin and Arneill (2003), Farbstein and Farling (2006), Sternberg and Wilson (2006), and Heschong (2003b) | Sternberg and Wilson (2006), Beauchemin and Hays (1996), and Schweitzer et al. (2004) |
| Presence or absence of visual cues (e.g., interior or exterior landmarks, visible entrance) literature consensus: visible external landmarks and entrance reduce stress | Ulrich et al. (2008), Beukeboom et al. (2012), Sternberg and Wilson (2006), Baker and Bernstein (2012), Dara-Abrams (2014), and Berto (2014) | Golledge (1992), Janzen and Jansen (2010), Lingwood et al. (2015), Parsons et al. (1998), and Ulrich et al. (2008) |
| Presence or absence of natural daylight literature consensus: natural daylight reduces stress | Ulrich (1984), Ulrich et al. (2008), Heschong (2003a, b), and Geiser and Walla (2011) | Boubekri et al. (1991), Devlin and Arneill (2003), Evans (2003), and Küller and Lindsten (1992) |
| Color of surfaces and openness in spaces literature consensus: dark colors increase stress | Devlin and Arneill (2003), Farbstein and Farling (2006), and Hidayetoglu et al. (2012) | Kwallek et al. (1988) and Stone and English (1998) |

visible entrance), presence or absence of natural daylight, and color of surfaces and openness in spaces. Some of these design features also indicate the level of restorativeness (i.e., mode of meditation and relaxation) on the other scale. These features were also confirmed through an ethnographic study conducted by 18 architects with diverse backgrounds in design with an average of 20 years of experience, as discussed in Ergan et al. (2018) paper.

### *Methods Used to Evaluate Human Physiological and Psychological Responses*

Various metrics have been proposed to understand the implications of visual stimuli and architectural layouts on emotional and physiological states of human beings (Parsons et al. 1998). Commonly used metrics include heart rate, blood pressure, and startle reflex to measure human emotional experiences such as stress, pain, anxiety, and memory (Bar et al. 2003; Parsons et al. 1998). A body area sensor network, representing a collection of biometric sensors, is a set of biometric wearable sensing devices connected to a system through wireless networks (Ullah et al. 2012), and has enabled researchers to measure and monitor such metrics and to relate those metrics to the events and stimuli presented to the subjects. Human experience is assessed on two scales as valence and arousal. Valence is defined as the differentiation of an emotion (e.g., stressed–relaxed, happiness–sadness) in the positive to negative scale, whereas arousal is defined as the intensity of that emotion (Chen et al. 2015; Geiser and Walla 2011). Table 2 provides an overview of commonly used biometric sensors at the intersection of the neuroscience and architecture domains. The level of effort to deploy refers to how easy it is to acquire the equipment and utilize in a nonmedical research setting.

As summarized in Table 2, EEG is an electrophysiological monitoring tool to record the electrical activity of the brain by placing electrodes along the scalp (Klonowski 2009). EEG helps in obtaining insights into how the human brain works and reacts toward different spatial settings. The benefits of using EEG come from the fact that it is noninvasive, is easy to deploy [as compared with functional magnetic resonance imaging (fMRI), positron-emission tomography (PET), and magnetoencephalography (MEG)], and can provide high quality and good time resolution of brain activity (Clemente et al. 2014; Pham and Tran 2012). It is also considered one of the most intensive biometric research tools since it provides data for both emotional valence and arousal. It has been utilized in mental work load analysis of construction workers (e.g., Chen et al. 2017) as well as the valence of construction workers under different work conditions (e.g., Jebelli et al. 2017) with accurate data captured from EEG headsets. However, analysis of EEG data is complicated due to unknowns of signal interpretations on different regions of the brain, and the interpretation of the data requires supporting data on other biometric sensors to get conclusive results. This sensor can be easily combined with VEs for emotional experience detection and quantification; however, this will not be solely enough to categorize complex human emotions.

GSR is also a biometric tool, powerful to measure a widely referred to metric called skin conductance. GSR provides data on the amount of sweat secretion from the skin, and is reported to have a positive correlation with the magnitude of emotional arousal (Villarejo et al. 2012) as shown in Table 2. As people are exposed to emotional events (e.g., stress, pleasure) in their daily life, emotional sweat levels increase, thus increasing the skin conductance response (SCR) as sweat levels increase (Benedek and Kaernbach 2010). The data that are captured by a GSR sensor are a combination of a slowly varying SCR, which is known by the tonic activity, and a faster-varying skin conductance response, which is known by the phasic activity. In order to be able to see the change in the human SCR, the event-related phasic activity must be separated from the tonic activity to be able to measure the change in human SCR peaks that occurred due to a stimulus.

A PPG sensor uses electrical signals derived from light reflected due to changes in blood flow during heart activity. Heart rate variability (HRV) is also an indicator of the emotional response triggered by an environment. Emotional states could have a significant impact on HRV when activity levels are controlled. Studies utilized HRV data to monitor operator physiology to minimize injuries (e.g., Shen et al. 2017). With PPG sensors, HRV data can be reliably derived as *R*-peak intervals with millisecond accuracy, so that meaningful HRV data can be obtained with short-duration measurements. However, utilization of the HRV metric alone will not be enough to capture human experience and should be paired up with other biometric sensors to get a holistic understanding of human experience.

In addition to these metrics, facial electromyography (f-EMG), which measures facial muscle activity by detecting and amplifying the small electrical impulses that are generated by specific facial muscles (i.e., corrugator and zygomatic muscles), and eye tracking provide researchers with facial expression and visual attention of a human in the surrounding environments. As shown in Table 2, they are easy to acquire and deploy as compared with other sensors listed. The inclusion of multiple sensor suites in the experimentation was for the purpose of having conclusive and complementary results for measuring stress and anxiety. As shown in Table 2, not every sensor is capable of measuring valence (a particular emotion) and arousal (intensity of the emotion) together. Hence, multiple sensors are needed to understand if they complement each other in the way they indicate valence or arousal.

In summary, given all these sensors available and what they measure, the platform includes all these sensors that are easy to deploy

**Table 2.** Overview of common biometric sensors used in neuroscience for architecture

| Sensor | Primary data captured | Valence or arousal | Effort required to analyze data | Level of invasion and effort to deploy | Focus |
|---|---|---|---|---|---|
| EEG | Brain activity | Valence and arousal | High | Noninvasive/easy | Electrical brain activity |
| GSR | Skin conductance | Arousal | Medium | Noninvasive/easy | Skin conductance response |
| PPG | Heart activity | Arousal | Medium | Noninvasive/easy | Change in HRV |
| f-EMG | Facial muscle reactions | Valence and arousal | High | Noninvasive/easy | Facial reactions |
| Eye-tracking | Eye movement | Valence and arousal | High | Noninvasive/easy | Fixation zones and points of interest |
| fMRI | Brain activity | Valence and arousal | High | Noninvasive/hard | Blood flow of neural activity |
| Electrocardiogram (ECG or EKG) | Heart activity | Arousal | High | Noninvasive/hard | HRV and HR |
| MEG | Brain activity | Valence and arousal | High | Noninvasive/hard | Magnetic neural activity |
| PET | Brain activity | Valence and arousal | High | Invasive/hard | Nuclear imaging of brain |



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**Table 3.** Values set for each of the architectural design features in VEs

| Architectural feature | VE1 (positive) | VE2 (negative) |
|---|---|---|
| Level of luminance | Standard lighting conditions (light intensity set above average, intensity >3.5 in the gaming engine) | Poor lighting conditions (lighting intensity set below average) |
| Color of surfaces and openness in spaces | Bright colors (light bounce intensity set above average, 2.0 in Unity 3D) | Dark colors (light bounce intensity set below average) |
| Natural daylight | Sufficient amount of natural daylight (has windows in measured room) | Significantly less amount of natural daylight (no window in measured room) |
| Visual cues | Visible external landmarks and entrance | No visible external landmarks |



and have in a visualization laboratory (Table 2, highlighted sensors are EEG, GSR, PPG, f-EMG, and Eye-tracking). The sensors used in the user experiments are noninvasive, compatible with a VR setup, and easy to purchase, use, and conduct data analysis. Moreover, the sensors used complement each other, so it is possible for the researchers to get a good understanding of what a user is experiencing in an architectural setting. Extensive discussions with neuroscientists, environmental psychologists, and biomedical engineers, and rigorous literature review in the field suggest that for measuring stress and anxiety, scientists refer to lower values in the beta, alpha, and theta bands as indications of restless and stressful mind (as also detailed in Table 5). Similarly, perspiration has been used as a metric to measure arousal for either anxiety or joy and the number of peaks in GSR is often used as a parameter to measure such arousals of subjects, where a high number of peaks indicates the subject is experiencing anxiety (or happiness) and is less relaxed (or excited). Hence, the correct interpretation of the user experience requires coupling of this sensor with other sensor suites that can measure valence (i.e., the type of experience). Another indication of stress or anxiety in the human body is the heart rate variability, which is similar to perspiration and is only related to arousal (for positive or negative experiences) and requires additional sensors to label the experience correctly. The most used parameter to measure variability is the average normal sinus to normal sinus interval (AVNN), where the higher the AVNN score, the more relaxed a subject. This parameter can be obtained from PPG or electrocardiogram (ECG) sensing. In this paper, we provide results for EEG, GSR, and PPG measurements as part of the integrated BSN.

## Methodology

The null hypothesis of this study is that the architectural design features used (i.e., the features that are deemed to be related to stress and anxiety) and how they are configured in design cannot impact stress levels and hence the human experience in a space. If the analysis of a sensor rejects the null hypothesis, the alternative hypothesis (i.e., the design features can impact human emotions) can be proven statistically. Since body area sensor measurements may change in VR settings as compared with the real spaces, we did not report back on the absolute values of the measurements in each sensor but reported the percent changes in the measurements as the quantification of impact of design configurations while participants work in two VEs.

This section presents the details of the prepared test beds and the design of the experiment to quantify the impact of the configured virtual spaces on measuring human experience. Although the integrated platform is generic for measuring different types of human experience, the VEs provided in this paper are specific to measuring the stress and anxiety level of people in designed spaces.

### *Preparation of the VEs for Experiments*

To test the hypothesis, the authors generated two VEs corresponding to the two ends of the scale for positively configured (i.e., stress-reducing or relaxing) and negatively configured (i.e., stress-inducing or stressful) environments as shown in Table 3. The main idea to focus on these two settings was to evaluate if the emotional responses received in these two settings are statistically significant or not and then to evaluate the difference when VEs are configured with variations between the two extreme ends. The architectural design features of level of luminance, natural daylight, color of surfaces and openness of spaces, and presence or absence of visual cues were configured to reflect two ends on a semantic scale of relaxing (positive) to stressful (negative). The first VE (i.e., VE1) was configured as the stress-reducing environment, where the environment had a sufficient amount of natural daylight, a standard level of luminance, bright colors on all the interior walls, and visible exterior landmarks and an entrance. On the other hand, the second VE (i.e., VE2), which was the stress-inducing environment, had significantly less daylighting, poor lighting, dark colors on all the interior walls, and less or no outdoor landmarks. Table 3 summarizes the values set for each feature in the virtual environments. Minimum and maximum intensity levels of lighting available in the gaming engine were selected to generate the stress-inducing and stress-reducing environments.

Environmental psychologists find the studies that isolate stimuli given to participants in user studies not reflective of the actual activations in human physiological parameters that would happen in naturalistic settings. Since this study was aiming at the human experience in spaces, the decision was to keep the spaces where architectural design features were altered as realistic as possible, and only configure the design features being evaluated. The reasoning behind having realistic spaces was due to this concern of the environmental psychologists.

VEs were generated using the BIM of a real educational facility. The geometry of both environments was obtained from the BIM, and materials and lighting configurations were rendered in a rendering platform. Each model with the rendered materials and lighting configurations was imported to a gaming engine, in which interactions with the models and a first-person controller were created to enable subjects to interact and navigate in the VEs. Fig. 2 shows screenshots from these two VEs.

A 249 cm (98-in.) touch screen and a motion-tracking solution, composed of optical cameras (with a capability to capture speeds up to 240 frames per second), an Apex interactive controller device (Vicon Motion Systems, Oxford, UK), and three-dimensional goggles were used to track subjects as participants navigated in the VEs, as shown in Fig. 3. A front camera captured participants' facial expressions as an additional data source for EMG muscle activities, and a back camera captured the VE interactions with the same time stamp of the eye-tracking solution (Fig. 3). The sensors used as part of the



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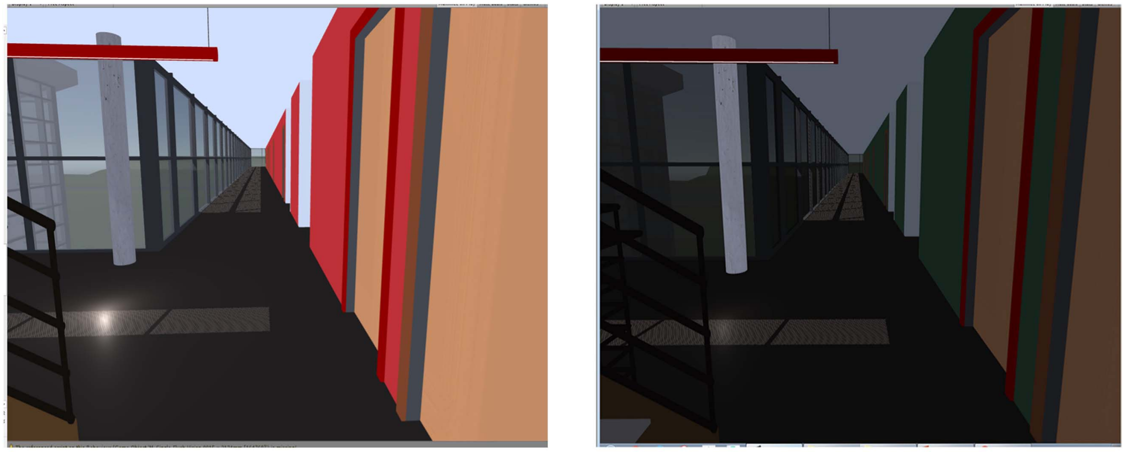
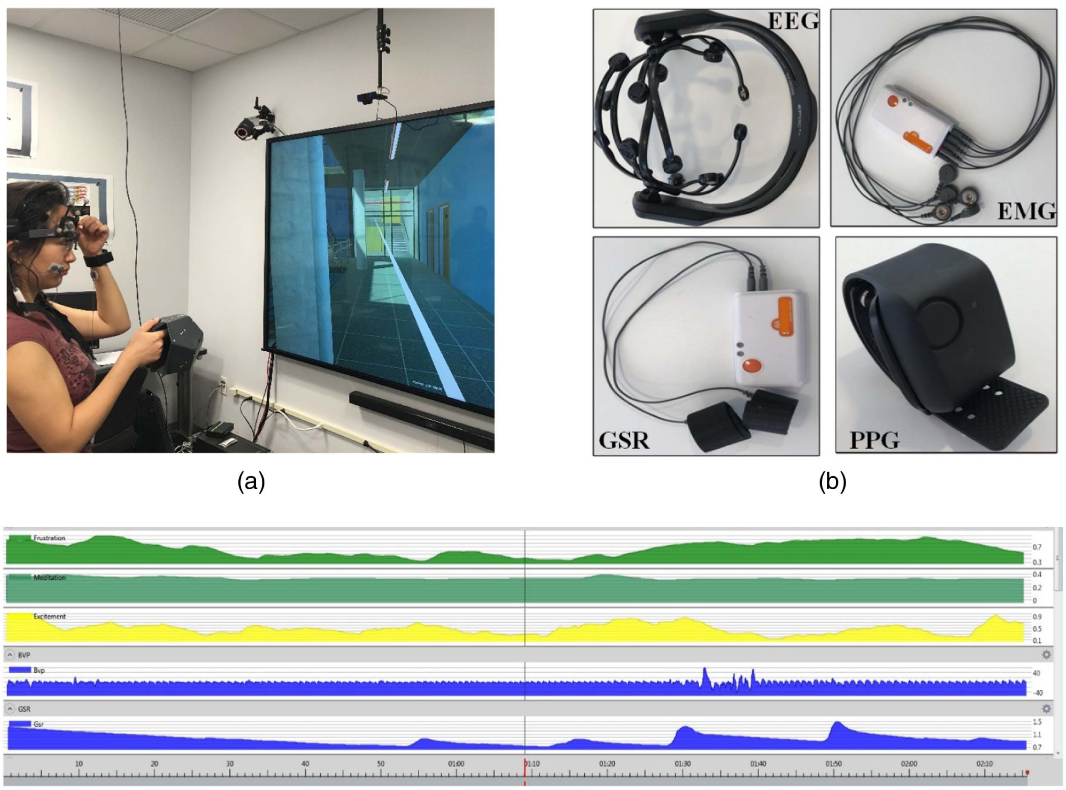


(a) (b)

**Fig. 2.** Screenshots from VEs: (a) VE1, which represents the stress-reducing environment; and (b) VE2, which represents the stress-inducing environment.




(a) (b)

(c)

**Fig. 3.** VR and BSN setup for experiments: (a) user navigating in virtual environments; (b) body area sensors used for bodily state data collection; and (c) real time sensor readings.

BSN and analyzed in this paper are provided in Fig. 3(b). The subjects' physiological data were captured throughout the experiment and stored in a platform that enabled integrated storage of the data from all sensors for each participant over time. Fig. 3 also shows the live data captured and plotted during the experiments.

### *Design of the Integrated VE and BSN Experiment*

The experiment was designed to capture the BSN data of participants while they complete tasks in each VE, and while the participants sit down and do nothing to capture their baseline biometric data. Fig. 4 summarizes the experiment setup and duration allocated for each step. First, participants were allowed to play with the VR setup and get used to the tools and the VR platform. Then subjects were informed about what they would do and the experiment work flow as detailed in Fig. 4.

At the beginning of the experiment, each subject was asked to sign a consent form and fill out a computer-based demographics survey (i.e., age, gender, level of education, occupation, and previous experience with VR). The questions in the paper-based

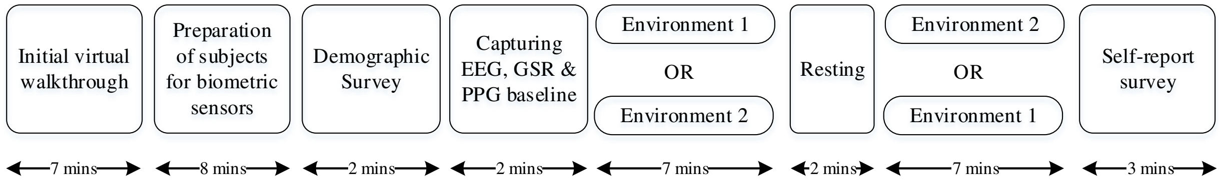



**Fig. 4.** Experimental setup for quantifying the impact of architectural design features on human experience.

self-report asked subjects about their preference of the environment [e.g., which space is preferred, which environment is easier to perform the tasks in, ranking the impact of the architectural features on them, and rating of each environment using a set of scales (relaxed or tense, focused or distracted, pleasant or unpleasant)]. A baseline period of 2 min was defined in the experiment, where participants sit and do nothing to capture their bodily states using the biometric sensors. This baseline data are important to have to compare the two environments with respect to individuals' in situ states.

Each participant starts at the entrance of the building, then performs the first task, which is to find a specific room (i.e., Room A) on the third floor of the building. Once the subject goes inside the room, the participant is required to find the thermostat in that room and check its temperature and adjust it. Then, instructions prompt the subject to find Room B to be able to adjust the temperature of Room A.

### Overview of Participants

Data were collected from a total number of 40 subjects, who were recruited in the experiment from students, faculty, and staff members at a university campus. Only 33 who had complete biometric data were included in the analysis. The effect size calculations showed that 32 subjects were sufficient to have a 5% significance level using a two-tailed t-test, with a standard deviation of 0.19. All subjects were in the age range between 21 and 30 years old, including 22 males and 11 females.

### Summary of Sensor Data Analysis

To quantify the architectural design features' impact on human experience in virtual environments, the authors conducted data analysis for every sensor used in the experiment (i.e., EEG, PPG, and GSR) individually. Table 4 provides a summary of the raw data collected by the sensors and the measurements the authors used in the data analysis process. For each sensor, the raw data were first normalized against the baseline period (i.e., where the participants were sitting still with no activities) to eliminate the differences among subjects so that the results could be comparable across participants. For EEG, the authors conducted power spectrum analysis by transforming the time-series data to the frequency domain. The authors then looked into various frequency bands [e.g., delta (0–4 Hz) and alpha (8–14 Hz)] to find if the design features have any impact on the brain activities of the subjects. For GSR data, the authors first categorized the participants into groups based on their baseline data. Then the number of GSR peaks were counted for each participant to find the relationship between GSR peaks and design features. For PPG, the authors conducted analysis on the average interbeat interval (IBI) (AVNN) to investigate if the design features had an impact on the human cardiac performance. The data analysis period was selected as the period when the subjects were exposed to the environments for at least 2 min and focused on the period when the subjects were navigating in between two targeted rooms. This period was selected since the subjects were exposed to the environment for a while, so that the impact of the design environment can be reflected on the bodily measurements of the subjects.

## Analysis of Data and Results

This section presents the results of the experiment as well as the type of analysis used for each sensor. The results are discussed per sensor data in the following subsections.

### Analysis and Results of EEG Data

The analysis of EEG data was performed in two ways, as power spectrum analysis by analyzing individual signal activity on each channel of each respondent on each frequency band, and then as lateralization by analyzing the pairs of channels symmetrically located in the left and right hemispheres of the brain. The EEG headset incorporates 14 channels positioned on the international 10–20 system, as shown in Fig. 5, with a sampling rate of 128 Hz.

The raw EEG signal from all channels was analyzed to calculate and plot power spectrum diagrams to quantify the differences in EEG signals in each environment. A power spectrum diagram

**Table 4.** Sensor measurements and definitions of metrics used in the analysis

| Sensor | Raw data captured | Analysis metrics | Definition |
|---|---|---|---|
| EEG | Oscillations in 14 channels of the EEG headset in the time domain | Power spectrum | A power spectrum diagram shows EEG signals in the frequency domain and describes the distribution of power in frequency bands |
| | | Frequency bands | Representation of EEG oscillations in the frequency domain instead of the time domain; includes delta (0–4 Hz), theta (4–8 Hz), alpha (8–14 Hz), beta (14–40 Hz), and gamma (40 Hz and above) bands |
| GSR | SCR: fast-varying skin conductance caused by external stimulations | SCR peaks | SCR signal jump higher than the defined threshold (i.e., onset amplitude) |
| | | Peak amplitude | Amplitude at the peak minus the defined threshold (i.e., onset amplitude) |
| PPG | HRV: variation of the time interval between subject's heartbeats | Interbeat interval (IBI) | The time between consecutive heart beats measured in milliseconds |
| | | AVNN score | Average of the normal sinus (i.e., heart rate of 60–100 beats per minute) intervals |

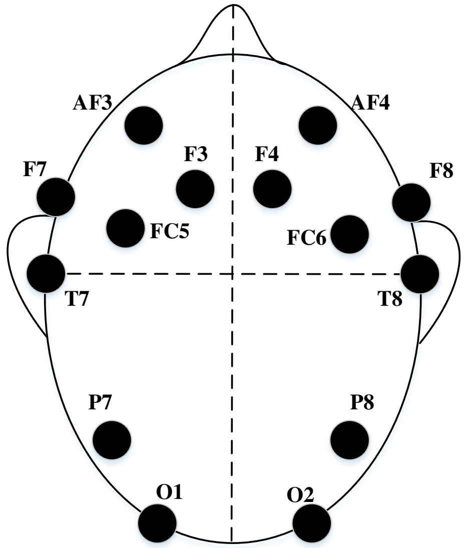



**Fig. 5.** Distribution of EEG channels across the scalp.

describes the distribution of power in frequency bands, which are delta (0–4 Hz), theta (4–8 Hz), alpha (8–14 Hz), beta (14–40 Hz), and gamma (40 Hz and above). To generate power spectrum diagrams, first the raw EEG signal of each participant was normalized against their baseline signals. For a given participant's EEG data, this normalization included calculating the mean value of EEG signals collected during the baseline period and dividing the EEG signals captured beyond the baseline period by the mean value of the baseline period. The goal of this normalization was to bring different subjects' EEG data to a comparable scale. Next, the fast Fourier transformation (FFT) procedure was conducted using a moving window of 1 s to convert the EEG signal from the original time domain to the frequency domain. The signal was then filtered to remove any noise using a high-pass filter of 0.5 Hz and a low-pass filter of 50 Hz in order to calculate the power of each channel, and hence the power of the different frequency bands. For each participant, the average normalized power across time was calculated for the EEG signals on each channel in each frequency band. The frequency band boundaries are shown with vertical lines in the plot. An example power spectrum diagram for a participant for each channel is provided in Fig. 6. An enlarged power spectrum diagram for a channel is also shown on the right with frequency bands highlighted. The analysis for all the sensor data was defined as the room period, indicating the time when a subject leaves the first target room in the VE and finds the second target room. The idea was to focus on a time period where participants had enough exposure to the virtual space after they enter the building (start of the experiment) and this exposure is reflected in their biometric data.

These oscillations were then interpreted based on the earlier findings in neuroscience regarding their meanings across participants. Table 5 shows a summary of these general interpretations

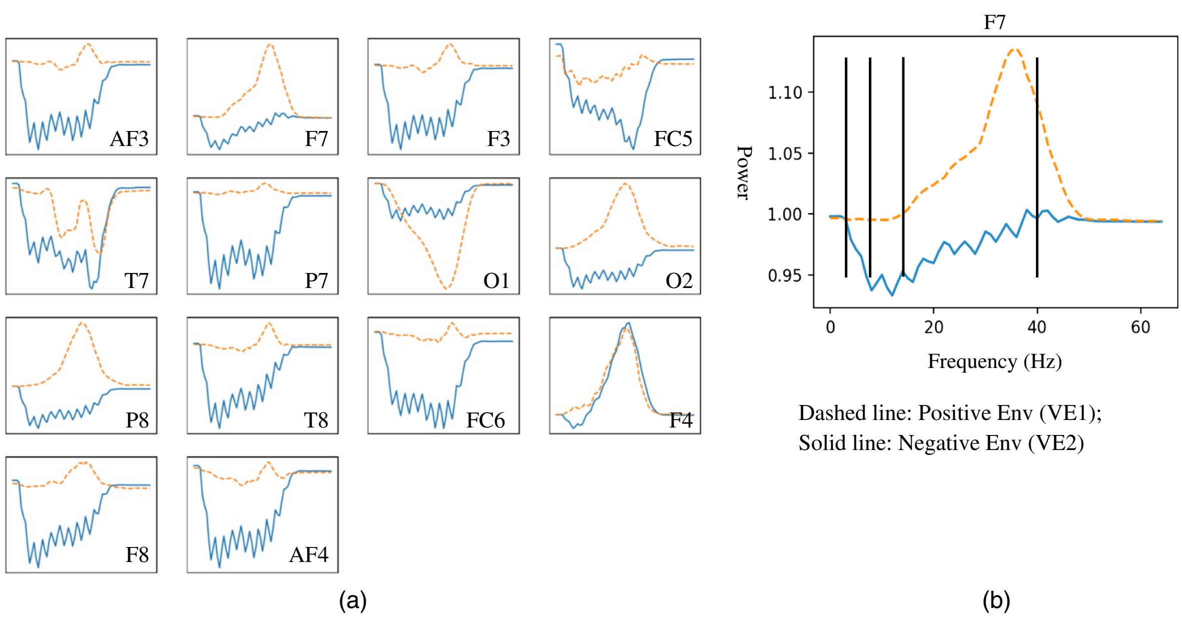



**Fig. 6.** Power spectrum plot for a subject. The analysis period is when a subject leaves the first target room in the VE and finds the second target room.

**Table 5.** Interpretive meanings of EEG signal oscillations on different frequency bands

| Human experience | Frequency bands | Channels to analyze in detail | Expected behavior | References |
|---|---|---|---|---|
| Stress and anxiety | Alpha (8–14 Hz) | All channels or frontal alpha (F3/F4 or F7/F8) | Higher alpha in VE1 (lower in VE2) Higher alpha in VE1 (lower in VE2) | Gevins et al. (1979) and Lin et al. (2010) |
| | Beta (14–40 Hz) | All channels | Higher beta in VE1 (lower in VE2) | Aftanas et al. (2002), Ahern and Schwartz (1985), CherylK (2009), and Onton et al. (2005) |
| | Theta (4–8 Hz) | All channels or frontal theta | Higher theta in VE1 (lower in VE2) | Gevins et al. (1979) and Lin et al. (2010) |

**Table 6.** Percentage of participants that showed statistically significant difference in EEG signal data in VE1 and VE2 for each channel across all frequency bands

| Channel | Delta | Theta | Alpha | Beta | Gamma |
|---|---|---|---|---|---|
| F7 | 73 | 90 | 93 | 97 | 97 |
| F8 | 70 | 77 | 93 | 100 | 93 |
| F3 | 77 | 83 | 87 | 97 | 87 |
| F4 | 90 | 83 | 97 | 93 | 97 |
| FC5 | 87 | 80 | 90 | 87 | 97 |
| FC6 | 70 | 87 | 97 | 93 | 97 |
| AF3 | 77 | 93 | 93 | 97 | 100 |
| AF4 | 80 | 77 | 93 | 97 | 90 |
| T7 | 80 | 73 | 97 | 90 | 87 |
| T8 | 80 | 83 | 90 | 100 | 97 |
| P7 | 77 | 83 | 97 | 100 | 90 |
| P8 | 67 | 87 | 87 | 97 | 93 |
| O1 | 80 | 73 | 90 | 93 | 97 |
| O2 | 63 | 93 | 93 | 97 | 93 |

of these oscillations on the frequency bands for increased stress or anxiousness. Higher theta and alpha bands are typically correlated with meditation and relaxation moods in the literature (e.g., Gevins et al. 1979; Lin et al. 2010), especially for frontal channels (i.e., F3/F4 and F7/F8). On the other hand, lower beta band power (14–40 Hz) is generally known to be correlated with active, busy, or anxious thinking (e.g., Aftanas et al. 2002; Ahern and Schwartz 1985).

When the power spectrum diagrams were analyzed across participants, it was apparent that there were statistically significant differences in oscillations on each channel when participants were in VE1 and VE2. A paired sample $t$-test at the 95% confidence interval compared the mean responses of subjects for each channel between the two VEs. The results conducted for each participant separately on each channel across frequency bands (i.e., delta, theta, alpha, beta, and gamma) showed significant difference between the two environments as shown in Table 6. The percentage was calculated by using the number of participants that showed significant difference in EEG signal data divided by the total number of participants.

Results of the raw data analysis on each channel across participants (Table 6) show that a high number of people (more than 70% and up to 100%) showed oscillations in the alpha, theta, and beta bands across frontal channels that are statistically significantly different in each VE. This result was the same for the frontal channels for all frequency bands. Given that the EEG data were statistically significantly different for a majority of the participants in each VE, the next step was to understand if oscillations were higher in the VE1 (positive) as compared with the VE2 given the expectations in Table 5. EEG data across participants and across channels were analyzed for each frequency band (by examining the power spectrum plot of each participant). The results show that on average, 40% of the oscillations were higher across all channels in the positively configured environment (VE1) as compared with VE2 in all frequency bands. The normalized oscillations ranged between 0.01 (which occurred at the theta band) and 0.63 (which occurred at the beta band) when all EEG data from participants were analyzed in positive and negative environments. Overall, the results of EEG analysis indicate that the positively configured environment was stress reducing as compared with the negative environment.

The built-in algorithms in the EEG module calculate the level of frustration, engagement, and excitement using the captured data on all channels. As expected, results of the built-in algorithms showed a statistically significant difference in EEG oscillations in both environments, where engagement percentages were found to be 7.2% higher in the positive environment (VE1), while frustration or stress percentages were found to be 22% higher in the negative environment (VE2). To sum up, across all participants, the oscillations in brain signals were statistically significantly different in two VR environments; and 40% of the EEG oscillations were higher on theta, alpha, and beta frequency bands in the positive environment as compared with the negative one. In conclusion, the result concurs with the hypothesis that the subjects experience a statistically different EEG response between the positive and negative virtual environments, with more than 40% of the data showing higher EEG power spectrum in the positive environment in alpha, theta, and beta bands.

### Analysis and Results of GSR Data

A GSR sensor was used in this study to measure the GSR in units of microsiemens. The sampling frequency was set to 104 Hz. Disposable Ag/AgCI electrodes were placed on the palm side of the index finger and the middle finger of the nondominant hand of the subject to avoid any noise from moving the hand in the task.

The data were analyzed by determining the number of peaks in the SCR that subjects experienced during the experiment based on the following logic. The phasic data (SCR), which correspond to a faster-varying skin conductance data component (fluctuating within seconds), were extracted from the GSR signal by using an averaging sliding window. The averaging sliding window computed the median GSR for 4,000 ms centered on a current sample. This value was then subtracted from the current sample to get the phasic data. Peak onset and offset thresholds were set to 0.01 and 0 $\mu$S (Benedek and Kaernbach 2010). Peak onset value represents the starting point in time where a peak is detected, while the offset value represents the time when a peak has passed. To avoid false positives, the onset value was not counted if it was less than 0.01 $\mu$S. The maximum original GSR data within each pair of onsets and offsets was a SCR peak. GSR peak amplitude is the amplitude at the peak minus the amplitude at onset. A peak was only considered if its amplitude was higher than the threshold amplitude by 0.005 above the onset value. Also, a signal jump threshold that accounts for false peaks—caused by noise—was set to 0.02 $\mu$S (Barnett 2008).

GSR peaks and amplitude graphs were analyzed for all subjects in groups. These groups were defined based on their baseline performance in the experiment because the SCR value could vary among individuals, and one fixed SCR window would not be able to best represent all participants. Group 1 (13 participants) included people with baseline $<2$ $\mu$S, Group 2 (15 participants) included people with baseline 2 $\mu$S $\leq$ SCR $\leq$ 10 $\mu$S, and Group 3 (3 participants) included people with baseline SCR $>$ 10 $\mu$S. Since Group 3 only included three participants, their results are not presented and were excluded from conclusions. Fig. 7 shows the SCR plot for the first two groups on a fixed sample size with 200 resampled data points. Since the time it takes for each participant to complete the assigned tasks was different, the SCR data were not captured on the same length of time. Hence, the data were resampled and provided in a plot in Fig. 7.

As shown in Fig. 7, the SCR data showed differences in each VE and as compared with baseline values. The results support the expectations that SCR was higher in the negative environment (an indication of stress) as compared with the positive one, and higher as compared with their baseline values across participants in both groups.

Table 7 shows the average number of SCR peaks as well as the peak amplitude of all subjects during the baseline period,





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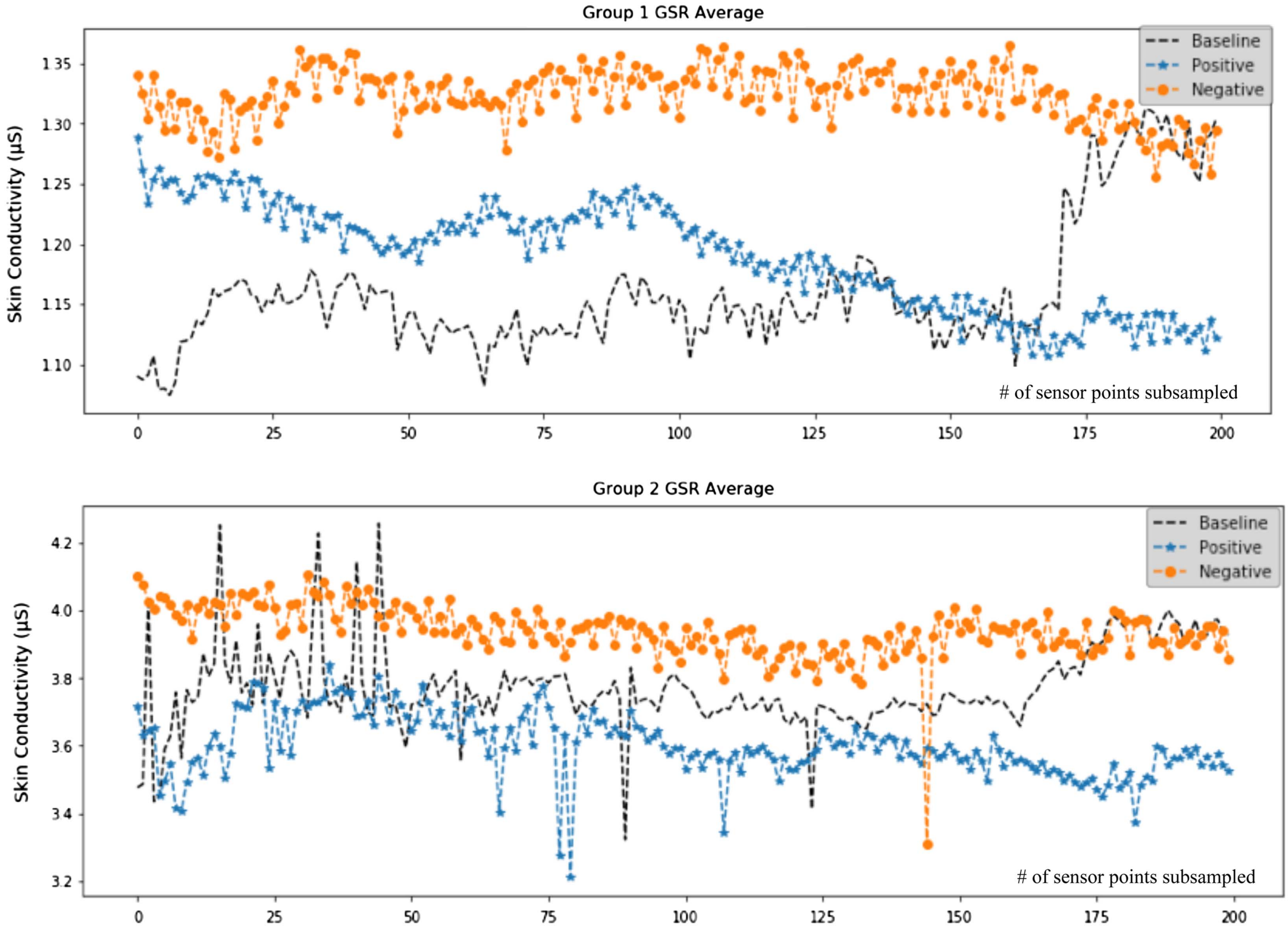


**Fig. 7.** Average SCR curve for Group 1 (baseline SCR < 2 $\mu$S) and Group 2 (2 $\mu S \le$ baseline SCR $\le 10$ $\mu$S) for the analysis period. Positive = VE1; and Negative = VE2.

VE1, and VE2. As expected, it can be seen that the average number of SCR peaks as well as the amplitude of the peaks increased from the baseline to VE1 and to VE2. The average number of peaks in VE1 increased by 154% as compared with the baseline and by another 141% from VE1 to VE2. Moreover, the number of peaks/minute in VE1 increased by 159% from the baseline and by 93% from VE1 to VE2. These results, when coupled with EEG analysis, can be interpreted for increased anxiousness (higher emotional response) with respect to the baseline, with more impact in the negative environment (Villarejo et al. 2012).

A paired sample statistical $t$-test was conducted to assess the statistical significance of the differences between the previously mentioned scores. The results of the $t$-test are summarized in Table 8 for 95% confidence interval, and state that the difference between the SCR data is statistically significantly different in each environment (with the negative environment having higher emotional response) and as compared with the baseline GSR data.

**Table 7.** Analysis of GSR data across participants

| SCR parameters | Baseline | VE1 (positive) | VE2 (negative) |
|---|---|---|---|
| Average number of SCR peaks | 3.72 | 9.45 | 22.81 |
| Average number of peaks/minute | 6.09 | 15.77 | 30.49 |
| Peak amplitude ($\mu$S) | 0.036 | 0.042 | 0.044 |

## Analysis and Results of PPG Data

HRV reflects the variation of the time interval between a subject's heartbeats. The IBI is the time between consecutive heart beats and is measured in milliseconds. A PPG wristband was utilized to measure the HRV at 64 Hz. The analysis of IBI data was based on the AVNN analysis to identify their emotional response. A normal sinus is defined as a heart rate and rhythm of 60–100 beats per minute. The higher the AVNN score, the more relaxed a person is. A change in AVNN scores as compared with the baseline values

**Table 8.** Paired $t$-test between VEs and baseline across participants

| SCR parameters | Paired samples | $p$-value (two-tailed) |
|---|---|---|
| Average number of SCR peaks | VE1–VE2 | 0.002 |
| | Baseline—VE1 | 0.004 |
| | Baseline—VE2 | 0.000 |
| Peak amplitude ($\mu$S) | VE1–VE2 | 0.085 |
| | Baseline—VE1 | 0.406 |
| | Baseline—VE2 | 0.540 |

**Table 9.** Average scores of AVNN across VEs

| Experiment period | Average IBI AVNN (ms) |
|---|---|
| Baseline | 692 |
| VE1 (positive) | 690 |
| VE2 (negative) | 683 |

**Table 10.** Paired *t*-test scores of AVNN across VEs

| Paired samples | *t*-score | *p*-value (two-tailed) |
|---|---|---|
| VE1–VE2 | 0.534 | 0.598 |
| Baseline—VE1 | 0.132 | 0.895 |
| Baseline—VE2 | 0.678 | 0.503 |

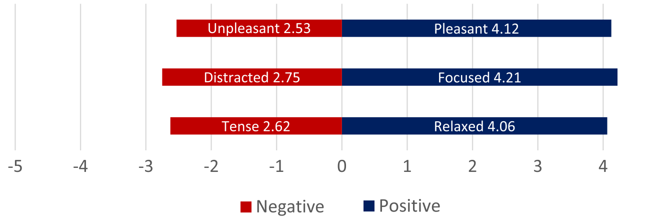


**Fig. 8.** Self-reporting scores across participants for each VE in given semantic scales.

also indicates the degree of realism in the VEs and can be used to analyze that aspect.

The average scores of AVNN for all subjects when different stimuli were presented are provided in Table 9. AVNN decreased by 2 ms in the positive environment (VE1) as compared with subjects' calm states (i.e., baseline values), and decreased even more in the negative environment (VE2). This decrease in AVNN in VE2 is attributed to increased stress in VE2 and concurs with the analysis of data from EEG and GSR.

Furthermore, a pairwise comparison *t*-test was conducted to assess the statistical significance of the difference between the scores that are shown in Table 10. The results show that at the 95% confidence level, although there was a trend in the data for increased emotional response in the negative environment as compared with the positive one (and both compared to the baseline scores), the difference between the AVNN scores in both environments and the difference of them with respect to the baseline scores were not statistically significant.

Overall, the analyses of the data across sensors support each other, with indications of higher emotional response in VE2 with respect to baseline values and values obtained in VE1 (positive). Although individual sensor analysis was not conclusive for stress indicators versus excitement, when the results were combined and compared with participants' baseline values, it was conclusive that VE1 was not stressful.

## Comparison of BSN Results with Subjective Reports

Without overburdening participants with VEs that represent incremental changes in evaluated design features, we directly aimed at quantifying the difference in two extreme ends of the bipolar scales utilized. Even if different VEs would be used, we would test the same set of architectural design features at these two extreme ends. That is why for external validity of the results, we aimed at having a pool of participants that would generate statistically significant results. We evaluated the sample size throughout the data collection phase to reach 33 participants to talk about statistical significance.

A self-report survey was developed to qualitatively assess the VEs presented to subjects and see if their self-articulated experience matched what their bodily states told us. Specifically, the participants were asked to select the environment they prefer and rate each environment on a bipolar scale that measures stress and anxiety, where 1 represented the most negative response and 5 represented the most positive response on a given bipolar scale. About 84% of subjects preferred to stay and to perform the task in the positively designed environment (VE1). The subjects were also asked to rank each VE on semantic scales (i.e., pleasant versus unpleasant, focused versus distracted, relaxed versus tense) designed to measure stress and anxiety (Fig. 8). The comparison of ratings for both environments showed that subjects found VE1 to be 50% more pleasant and focused, and about 60% more relaxing than VE2 as shown in Fig. 8.

The difference between both ratings was statistically tested for paired samples (VE1 and VE2) and showed that at the 95% confidence level, subjects experienced statistically significant positive emotions in VE1 as compared with VE2 on all semantic scales with *p*-values of 0. In general, these self-reports of participants align well with the quantified results from the biometric sensors that a positive environment is preferable and creates less stress and anxiety as compared with the environment that has less luminance, natural daylight, dark-colored surfaces, and no outside landmarks.

## Conclusions and Future Work

This paper provided the details of an integrated virtual reality and BSN platform to quantify the impact of architectural design configurations on human experience, and evaluated the platform on measuring the stress and anxiety level in designed spaces using EEG, GSR, and PPG sensors. Several architectural design features used in the experiments showed that when the architectural design features are configured to give a positive experience (relaxing), 7% more engagement, 22% reduction in frustration and stress levels, more theta (4–8 Hz), alpha (8–14 Hz), and beta (14–40 Hz) oscillations in almost all channels, and less perspiration and heart rate variability are experienced as compared with a space configuration for reflecting negative experience (stressful). Overall, the combined results of sensor data analysis show that there are strong indications that different architectural design configurations can reduce or induce the stress and anxiety experience to occupants of a given space.

The presence or absence of natural lighting, level of luminance in rooms, color of walls and openness of spaces, and the presence or absence of outside landmarks and a visible entrance can change the way people perceive the space, and this perception is reflected on the bodily measurements. The relative differences in sensor measurements in those spaces, which are configured to induce and reduce stress, are clear and prove the impact of the design features on people. This study provides the first findings on the quantification of such an impact of space design on people, where this impact has been widely known, but not yet quantified. Architects have also had instincts on how to configure a space to give a certain experience; however, they could not point to sources where these instincts had been tested and quantified.

Practitioners can utilize similar platforms of integrated VR and BSN to quantify the impact of their designs and conduct user studies with anticipated occupant groups before designs are finalized in order to deliver designs resulting in certain experiences. The future work of this research will be extended to include the analysis of other integrated biometric sensors (e.g., eye tracking, facial expressions) and measure human experiences beyond the sense of stress and anxiety (e.g., restorativeness, motivation to work) in architectural spaces.

## Acknowledgments

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## References

Aftanas, L. I., A. A. Varlamov, S. V. Pavlov, V. P. Makhnev, and N. V. Reva. 2002. "Time-dependent cortical asymmetries induced by emotional arousal: EEG analysis of event-related synchronization and desynchronization in individually defined frequency bands." *Int. J. Psychophysiol.* 44 (1): 67–82. https://doi.org/10.1016/S0167-8760(01)00194-5.

Ahern, G. L., and G. E. Schwartz. 1985. "Differential lateralization for positive and negative emotion in the human brain: EEG spectral analysis." *Neuropsychologia* 23 (6): 745–755. https://doi.org/10.1016/0028-3932(85)90081-8.

Andrée, K., D. Nilsson, and J. Eriksson. 2016. "Evacuation experiments in a virtual reality high-rise building: Exit choice and waiting time for evacuation elevators." *Fire Mater.* 40 (4): 554–567. https://doi.org/10.1002/fam.2310.

Baker, L., and H. Bernstein. 2012. *The impact of school buildings on student health and performance: A call for research*. Boston, MA: McGraw-Hill.

Bar, M., E. Aminoff, and E. Aminoff. 2003. "Cortical analysis of visual context." *Neuron* 38 (2): 347–358. https://doi.org/10.1016/S0896-6273(03)00167-3.

Barnett, K. J. 2008. "The effects of a poor night sleep on mood, cognitive, autonomic and electrophysiological measures." *J. Integrative Neurosci.* 7 (3): 405–420. https://doi.org/10.1142/S0219635208001903.

Beauchemin, K. M., and P. Hays. 1996. "Sunny hospital rooms expedite recovery from severe and refractory depressions." *J. Affective Disord.* 40 (1–2): 49–51. https://doi.org/10.1016/0165-0327(96)00040-7.

Benedek, M., and C. Kaernbach. 2010. "A continuous measure of phasic electrodermal activity." *J. Neurosci. Methods* 190 (1): 80–91. https://doi.org/10.1016/j.jneumeth.2010.04.028.

Berto, R. 2014. "The role of nature in coping with psycho-physiological stress: A literature review on restorativeness." *Behav. Sci.* 4 (4): 394–409. https://doi.org/10.3390/bs4040394.

Beukeboom, C. J., D. Langeveld, and K. Tanja-Dijkstra. 2012. "Stress-reducing effects of real and artificial nature in a hospital waiting room." *J. Altern. Complementary Med.* 18 (4): 329–333. https://doi.org/10.1089/acm.2011.0488.

Boubekri, M., R. B. Hull, and L. L. Boyer. 1991. "Impact of window size and sunlight penetration on office workers' mood and satisfaction: A novel way of assessing sunlight." *Environ. Behav.* 23 (4): 474–493. https://doi.org/10.1177/0013916591234004.

Butterworth, I. 2000. *The relationship between the built environment and wellbeing: A literature review*. Melbourne, Australia: Victorian Health Promotion Foundation.

Chen, J., J. E. Taylor, and S. Comu. 2017. "Assessing task mental workload in construction projects: A novel electroencephalography approach." *J. Constr. Eng. Manage.* 143 (8): 04017053. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001345.

Chen, M., J. Han, L. Guo, J. Wang, and I. Patras. 2015. "Identifying valence and arousal levels via connectivity between EEG channels." In *Proc., Int. Conf. on Affective Computing and Intelligent Interaction*, 63–69. New York: IEEE.

CherylK, K. 2009. "Stress & brain waves." Accessed January 10, 2018. http://americannutritionassociation.org/node/257.

Chokwitthaya, C., S. Saeidi, Y. Zhu, and R. Kooima. 2017. "The impact of lighting simulation discrepancies on human visual perception and energy behavior simulations in immersive virtual environment." In *Proc., ASCE Int. Workshop on Computing in Civil Engineering*, 390–398. Reston, VA: ASCE.

Clemente, M., A. Rodríguez, B. Rey, and M. Alcañiz. 2014. "Assessment of the influence of navigation control and screen size on the sense of presence in virtual reality using EEG." *Expert Syst. Appl.* 41 (4): 1584–1592. https://doi.org/10.1016/j.eswa.2013.08.055.

Dara-Abrams, D. 2014. "Learning and navigating built environments: How spatial cognition and behavior relate to environmental form." In *Proc., Movement and Orientation in Built Environments: Evaluating Design Rationale and User Cognition*, 1–8. Veracruz, Mexico: SFB/TR8 Spatial Cognition.

Devlin, A. S., and A. B. Arneill. 2003. "Health care environments and patient outcomes: A review of the literature." *Environ. Behav.* 35 (5): 665–694. https://doi.org/10.1177/0013916503255102.

Du, J., Y. Shi, Z. Zou, and D. Zhao. 2017. "CoVR: Cloud-based multiuser virtual reality headset system for project communication of remote users." *J. Constr. Eng. Manage.* 144 (2): 04017109. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001426.

Duarte, E., F. Rebelo, J. Teles, and M. S. Wogalter. 2014. "Behavioral compliance for dynamic versus static signs in an immersive virtual environment." *Appl. Ergon.* 45 (5): 1367–1375. https://doi.org/10.1016/j.apergo.2013.10.004.

Eberhard, J. P. 2009. *Brain landscape: The coexistence of neuroscience and architecture*. New York: Oxford University Press.

Edelstein, E. A., K. Gramann, J. Schulze, N. B. Shamlo, E. van Erp, A. Vankov, S. Makeig, L. Wolszon, and E. Macagno. 2008. "Neural responses during navigation and wayfinding in the virtual aided design laboratory brain dynamics of re-orientation in architecturally ambiguous space." In *Proc., Movement and Orientation in Built Environments: Evaluating Design Rationale and User Cognition*, 35–41. Veracruz, Mexico: SFB/TR8 Spatial Cognition.

Ergan, S., Z. Shi, and X. Yu. 2018. "Towards quantifying human experience in the built environment: A crowdsourcing based experiment to identify influential architectural design features." *J. Build. Eng.* 20: 51–59. https://doi.org/10.1016/j.jobe.2018.07.004.

Evans, G. W. 2003. "The built environment and mental health." *J. Urban Health* 80 (4): 536–555. https://doi.org/10.1093/jurban/jtg063.

Farbstein, J., and M. Farling. 2006. "Understanding cognitive processes in correctional settings." In *Proc., Neuroscience and Correctional Facility Design Workshop*. Washington, DC: American Institute of Architects.

Franz, G., M. von der Heyde, and H. H. Bülthoff. 2005. "An empirical approach to the experience of architectural space in virtual reality—Exploring relations between features and affective appraisals of rectangular indoor spaces." *Autom. Constr.* 14 (2): 165–172. https://doi.org/10.1016/j.autcon.2004.07.009.

Geiser, M., and P. Walla. 2011. "Objective measures of emotion during virtual walks through urban environments." *Appl. Sci.* 1 (1): 1–11. https://doi.org/10.3390/as1010001.

Gevins, A., G. Zeitlin, J. Doyle, C. Yingling, R. Schaffer, E. Callaway, and C. Yeager. 1979. "Electroencephalogram correlates of higher cortical functions." *Science* 203 (4381): 665–668. https://doi.org/10.1126/science.760212.

Golledge, R. G. 1992. "Place recognition and wayfinding: Making sense of space." *Geoforum* 23 (2): 199–214. https://doi.org/10.1016/0016-7185(92)90017-X.

Heschong, L. 2003a. *Daylight and retail sales*. Technical Rep. No. P500-03-082-A-5. Sacramento, CA: California Energy Commission.

Heschong, L. 2003b. *Windows and classrooms: A study of student performance and the indoor environment*. Technical Rep. No. P500-03-082-A-7. Sacramento, CA: California Energy Commission.

Heydarian, A., J. P. Carneiro, D. Gerber, B. Becerik-Gerber, T. Hayes, and W. Wood. 2015. "Immersive virtual environments versus physical built environments: A benchmarking study for building design and user-built environment explorations." *Autom. Constr.* 54: 116–126. https://doi.org/10.1016/j.autcon.2015.03.020.

Hidayetoglu, M. L., K. Yildirim, and A. Akalin. 2012. "The effects of color and light on indoor wayfinding and the evaluation of the perceived environment." *J. Environ. Psychol.* 32 (1): 50–58. https://doi.org/10.1016/j.jenvp.2011.09.001.

Höppe, P. 2002. "Different aspects of assessing indoor and outdoor thermal comfort." *Energy Build.* 34 (6): 661–665. https://doi.org/10.1016/S0378-7788(02)00017-8.

Janzen, G., and C. Jansen. 2010. "A neural wayfinding mechanism adjusts for ambiguous landmark information." *NeuroImage* 52 (1): 364–370. https://doi.org/10.1016/j.neuroimage.2010.03.083.

Jebelli, H., S. Hwang, and S. Lee. 2017. "Feasibility of field measurement of construction workers' valence using a wearable EEG device." In *Proc., ASCE Int. Workshop on Computing in Civil Engineering*, 99–106. Reston, VA: ASCE.

Klonowski, W. 2009. "Everything you wanted to ask about EEG but were afraid to get the right answer." *Nonlinear Biomed. Phys.* 3 (2): 1–5. https://doi.org/10.1186/1753-4631-3-2.

Küller, R., and C. Lindsten. 1992. "Health and behavior of children in classrooms with and without windows." *J. Environ. Psychol.* 12 (4): 305–317. https://doi.org/10.1016/S0272-4944(05)80079-9.

Kwallek, N., C. M. Lewis, and A. S. Robbins. 1988. "Effects of office interior color on workers' mood and productivity." *Perceptual Motor Skills* 66 (1): 123–128. https://doi.org/10.2466/pms.1988.66.1.123.

Lin, Y. P., C. H. Wang, T. P. Jung, T. L. Wu, S. K. Jeng, J. R. Duann, and J. H. Chen. 2010. "EEG-based emotion recognition in music listening." *IEEE Trans. Biomed. Eng.* 57 (7): 1798–1806. https://doi.org/10.1109/TBME.2010.2048568.

Lingwood, J., M. Blades, E. K. Farran, Y. Courbois, and D. Matthews. 2015. "The development of wayfinding abilities in children: Learning routes with and without landmarks." *J. Environ. Psychol.* 41: 74–80. https://doi.org/10.1016/j.jenvp.2014.11.008.

Onton, J., A. Delorme, and S. Makeig. 2005. "Frontal midline EEG dynamics during working memory." *NeuroImage* 27 (2): 341–356. https://doi.org/10.1016/j.neuroimage.2005.04.014.

Parsons, R., L. G. Tassinary, R. S. Ulrich, M. R. Hebl, and M. Grossman-Alexander. 1998. "The view from the road: Implications for stress recovery and immunization." *J. Environ. Psychol.* 18 (2): 113–140. https://doi.org/10.1006/jevp.1998.0086.

Pati, D. 2011. "A framework for evaluating evidence in evidence-based design." *Health Environ. Res. Des. J.* 4 (3): 50–71. https://doi.org/0.1177/193758671100400305.

Pham, T. D., and D. Tran. 2012. "Emotion recognition using the emotiv EPOC device." In *Proc., Int. Conf. on Neural Information Processing*, 394–399. Berlin: Springer.

Radwan, A., and S. Ergan. 2017. "Quantifying human experience in interior architectural spaces." In *Proc., ASCE Int. Workshop on Computing in Civil Engineering*, 373–380. Reston, VA: ASCE.

Rashid, M., and C. Zimring. 2008. "A review of the empirical literature on the relationships between indoor environment and stress in health care and office settings: Problems and prospects of sharing evidence." *Environ. Behav.* 40 (2): 151–190. https://doi.org/10.1177/0013916507311550.

Saeidi, S., A. Lowe, N. Johannsen, and Y. Zhu. 2017. "Application of immersive virtual environment (IVE) in occupant energy-use behavior studies using physiological responses." In *Proc., ASCE Int. Workshop on Computing in Civil Engineering*, 381–389. Reston, VA: ASCE.

Sanoff, H. 2001. *School building assessment methods*. Technical Rep. No. EF-005-904. Washington, DC: National Clearinghouse for Educational Facilities.

Schweitzer, M., L. Gilpin, and S. Frampton. 2004. "Healing spaces: Elements of environmental design that make an impact on health." Supplement, *J. Altern. Complementary Med.* 10 (S1): S-71 https://doi.org/10.1089/acm.2004.10.S-71.

Shen, X., I. Awolusi, and E. Marks. 2017. "Construction equipment operator physiological data assessment and tracking." *Pract. Period. Struct. Des. Constr.* 22 (4): 04017006. https://doi.org/10.1061/(ASCE)SC.1943-5576.0000329.

Skorupka, A. 2008. "Do you know your way? A mixed-method study on the use of virtual environments in wayfinding research." In Vol. 15 of *Proc., Movement and Orientation in Built Environments: Evaluating Design Rationale and User Cognition*, 21–33. Freiburg, Germany: SFB/TR8 Spatial Cognition.

Sternberg, E. M., and M. A. Wilson. 2006. "Neuroscience and architecture: Seeking common ground." *Cell* 127 (2): 239–242. https://doi.org/10.1016/j.cell.2006.10.012.

Stone, N. J., and A. J. English. 1998. "Task type, posters, and workspace color on mood, satisfaction, and performance." *J. Environ. Psychol.* 18 (2): 175–185. https://doi.org/10.1006/jevp.1998.0084.

Turpin-Brooks, S., and G. Viccars. 2006. "The development of robust methods of post occupancy evaluation." *Facilities* 24 (5–6): 177–196.

Ullah, S., H. Higgins, B. Braem, B. Latre, C. Blondia, I. Moerman, S. Saleem, Z. Rahman, and K. S. Kwak. 2012. "A comprehensive survey of wireless body area networks on PHY, MAC, and network layers solutions." *J. Med. Syst.* 36 (3): 1065–1094. https://doi.org/10.1007/s10916-010-9571-3.

Ulrich, R. 1984. "View through a window may influence recovery from surgery." *Science* 224 (4647): 420–421. https://doi.org/10.1126/science.6143402.

Ulrich, R. S., C. Zimring, X. Zhu, J. DuBose, H. B. Seo, Y. S. Choi, X. Quan, and A. Joseph. 2008. "Healthcare leadership: A review of the research literature on evidence-based healthcare design." *Health Environ. Res. Des. J.* 1 (3): 61–125.

van Leeuwen, J. P., and H. Wagter. 1997. "Architectural design-by-features." In *Proc., 7th Int. Conf. on CAAD Futures*, 97–115. Dordrecht, Netherlands: Springer.

Villarejo, M. V., B. G. Zapirain, and A. M. Zorrilla. 2012. "A stress sensor based on galvanic skin response (GSR) controlled by ZigBee." *Sensors (Switzerland)* 12 (5): 6075–6101. https://doi.org/10.3390/s120506075.

Western, J. C., A. Buttimer, and D. Seamon. 1981. "The human experience of space and place." *Econ. Geogr.* 57 (3): 275. https://doi.org/10.2307/143714.

Yildirim, K., A. Akalin-Baskaya, and M. Celebi. 2007. "The effects of window proximity, partition height, and gender on perceptions of open-plan offices." *J. Environ. Psychol.* 27 (2): 154–165. https://doi.org/10.1016/j.jenvp.2007.01.004.

Zou, H., N. Li, and L. Cao. 2017. "Emotional response-based approach for assessing the sense of presence of subjects in virtual building evacuation studies." *J. Comput. Civ. Eng.* 31 (5): 04017028. https://doi.org/10.1061/(ASCE)CP.1943-5487.0000679.

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# Multisensory stress reduction: a neuro-architecture study of paediatric waiting rooms

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**ABSTRACT**

The implementation of environmental satisfaction sources in the design of a health centre is a means to achieve stress reduction. The present work analyses the effect that these sources have on the stress reduction of patients' companions in a paediatric service. A two-phase study was carried out. During the first phase, 120 participants assessed 20 waiting rooms *in situ* in order to select the environmental sources with the greatest effect. During the second phase, the stress levels of 26 participants were measured in four simulated waiting rooms that combined the selected sources from the first phase. A multisensory simulation was carried out through a virtual reality experiment with visual, auditory and olfactory elements, and stress levels were measured at the psychological and neurophysiological levels. Results suggest that a combination of environmental satisfaction sources creates an important synergistic effect at the psychological and neurophysiological levels and underlines the importance of auditory and olfactory stimuli. Conclusions may be of interest to designers and managers of healthcare facilities.

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Waiting room design; healthcare; stress reduction; multisensory stimulation; neuro-architecture

## Introduction

Stress is an interrelation between a subject and the environment that occurs when the subject evaluates his or her resources as insufficient to meet the demands of the environment (Lazarus & Folkman, 1984). In healthcare, this state can cause a wide variety of negative effects that worsen patients' recovery and satisfaction (Ulrich, Quan, Zimring, Joseph, & Choudhary, 2004). Paediatric services represent a special challenge because of unforeseen behaviours and levels of stress that children may display (Gorski, Slifer, Kelly-Suttka, & Lowery, 2010). Despite the importance of stress in this context, 50% of patients still consider health centres stressful (Gates, 2008), suggesting that more needs to be done in the design and management of paediatric waiting rooms.

This stress not only affects patients but also extends to staff and patients' companions. Scholars have found that stress influences staff health (Devereux, Rydstedt, Kelly, Westo, & Buckle, 2004) and execution of errors (Scott, Hwang, & Rogers, 2006). A child's stay in hospital can also be highly stressful for companions. Among children's companions, stress is associated with a series of physical and psychological outcomes that include anxiety, depression, fatigue and interruption of sleep (Busse, Stromgren, Thorngate, & Thomas, 2013), which has further negative effects on the child (Whelan & Kirkby, 2000). Companions' stress has scarcely been studied, and, in the case of parents, mitigation measures are mainly based on their psychological preparation to face the situation.

Stress in healthcare facilities is caused not only by the illness and the related medical procedures but also by the context. Many studies have shown that it is possible to address the psychological state of patients and companions by means of space design (Leather, Beale, Santos, Watts, & Lee, 2003), which may even have a healing effect (Zhang, Tzortzopoulos, & Kagioglou, 2019). However, these studies generally have limitations: (1) they focus on analysing one isolated variable, whereas real spaces have a combination of variables (Andrade & Devlin, 2015); (2) the quantification of stress is carried out through self-reports, which are subject to biases (Schwarz & Strack, 1999) such as the participants' difficulty in expressing psychological status and (3) where environmental simulations are used as stimuli, they are usually photos or plans, which evoke different psychological responses from those evoked by the physical spaces that they represent (Higuera-Trujillo, López-Tarruella, & Llinares Millán, 2017).

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The objective of this study is to analyse the effect that certain characteristics of the design of paediatric waiting rooms have on companions' stress reduction, addressing the aforementioned limitations. Using neurophysiological and psychological measures, we analyse the effect of combinations of different environmental satisfaction sources on stress levels. Virtual reality was used for the environmental simulation. The choice of context was based on the fact that waiting rooms are spaces used by the general public and, in particular, that paediatric waiting rooms cause high levels of stress in children and their companions.

### The effect of healthcare facility design on stress

Various theoretical frameworks of healthcare environmental design and emotional support have been developed. In these frameworks, emotional support is interpreted as the actions carried out to support psychological needs and promote health and healing through the design of spaces in healthcare facilities (Schweitzer, Gilpin, & Frampton, 2004). One of the principal frameworks is Ulrich's theory of supportive design (1991). According to this framework, healthcare facilities have to foster three components: sense of control, social support and positive distractions. Many applied studies have been based on this framework. For example, it has been shown that different aspects of hospital rooms contribute to stress reduction (Andrade, Devlin, Pereira, & Lima, 2017) and that the sense of control affects companions in similar contexts to paediatric waiting rooms (Suter & Baylin, 2007). In addition to this framework, others have focused on taking account of patients' needs in the design process, citing 'interior design features', 'architectural features', 'maintenance features', 'social features' and 'ambient environment features' (Harris, McBride, Ross, & Curtis, 2002). In general, this discussion shows that interest in this dimension of health spaces has risen in recent times.

In most studies, the quantification of stress levels is carried out by means of self-report. This analysis, whether carried out through quantitative, qualitative or combined means (Higuera-Trujillo, Montañana i Aviñó, & Llinares Millán, 2017), is limited when registering participants' unconscious processes or when studying them in real time (Reinerman-Jones, Sollins, Gallagher, & Janz, 2013). Thus, the state reported by the user may differ from the reality, and state variations are difficult to study because the report covers a broad time segment. In this regard, the technologies applied in neuroscience can contribute by offering a higher level of objectivity. These technologies cover several manifestations of the nervous system. Among them are electrodermal activity (EDA), which measures variations in skin perspiration, electrocardiograms, which measure heart-rate variability (HRV), and electroencephalograms (EEGs), which measure variations in the electrical activity on the surface of the scalp. A considerable amount of literature has presented analyses to obtain stress metrics (Campbell & Ehlert, 2012). These analyses can enhance knowledge about stress reduction through design.

### Design variables

The environmental satisfaction sources studied in the literature focus on healthcare facilities and different sensory modalities. Accordingly, it is possible to find analyses focused on visual, auditory and olfactory variables.

In the visual modality, nature and design variables have been most frequently studied. In general, they can improve the user experience. They have been widely studied as sources of satisfaction, and they have even been proposed as therapy (Avrahami, 2006).

- Regarding nature, Ulrich (1991) proposed design patterns based on wild nature for healthcare facilities. Related studies have shown that this positive effect extends even to realistic nature photographs, reducing patients' stress (Nanda, Eisen, Zadeh, & Owen, 2011) and improving evaluations of waiting rooms (Beukeboom, Langeveld, & Tanja-Dijkstra, 2012).
- Regarding design, it has been shown that lighting, colour and architectural design variables generate the perception that better medical attention is being offered (Baker & Cameron, 1996). In this regard, it has been suggested that neuro-aesthetics can provide a source of pleasure in the healthcare environment (Nanda, Pati, & McCurry, 2009). The placement of furniture, even without modifying the architectural configuration, also has this capacity (Arneill & Devlin, 2002).

In the auditory modality, music and sounds of nature variables have frequently been studied both independently and in conjunction with visual ones. Including this type of stimuli can facilitate the health processes faced by the patient without negatively influencing the staff's responsibilities (Waldon & Thom, 2015).

- Music can contribute to reducing stress levels in both controlled laboratory conditions (Thoma et al., 2013) and in healthcare (Moola, Pearson, & Hagger, 2011). For example, it has been found that music reduces patients' pain in pre-operative (Lee, Chao, Yiin, Chiang, & Chao, 2011) and post-operative situations (Özer, Özlü, Arslan, & Günes, 2013) and in emergency service waiting rooms (Holm & Fitzmaurice, 2008). This stress-reducing effect has also been found in the case of companions (Routhieaux & Tansik, 1997).

- Sounds of nature can reduce the stress levels of patients (Saadatmand et al., 2013). It has also been found that they reduce the pain of invasive procedures combined with related visual stimuli (Diette, Lechtzin, Haponik, Devrotes, & Rubin, 2003).

In the olfactory modality, these stimuli have been found to have a positive effect on psychological and behavioural processes (Herz, 2009). A variety of scents have been studied, notably lavender and orange. However, although aromatherapy implementation in healthcare facilities has a long history and significant benefits (Cannard, 1996), this modality has been addressed by few studies.

- Lavender is one of the most frequently studied fragrances (Fenko & Loock, 2014). It has been observed to have benefits in reducing stress in neonatal (Kawakami et al., 1997), needle insertion (Kim et al., 2011), postpartum (Kianpour, Mansouri, Mehrabi, & Asghari, 2016), and palliative care contexts (Berger, Tavares, & Berger, 2013). In the staff sector, this scent also contributes to reducing stress (Sung & Eun, 2007) and improving performance (Birnbach, King, Vlaev, Rosen, & Harvey, 2013).
- The scent of orange, although it has been less widely studied, has been shown to reduce stress in healthcare facilities. Contexts where this effect has been observed include women waiting in the dentist's office (Lehrner, Eckersberger, Walla, Pötsch, & Deecke, 2000) and pregnant women in childbirth units (Rashidi-Fakari, Tabatabaeichehr, & Mortazavi, 2015).

More often than not, these studies use photographs or videos to simulate the environmental satisfaction sources. Although this approach may be valid, it has certain weaknesses. Among other weaknesses, photographs and videos lack interactivity, are subject to external distractors, and do not reproduce olfactory stimuli. Consequently, experience differs substantially from reality (de Kort, Ijsselsteijn, Kooijman, & Schuurmans, 2003). In this sense, virtual reality can contribute by generating multisensory experiences that are more similar to reality because it can provide visual, auditory and olfactory simulation. Thus, it offers the chance to develop experiences which generate a sense of presence or 'being there' (Steuer, 1992), in an immersive interactive simulation. Moreover, viewed in head-mounted displays (HMDs), visual information of the physical environment is completely replicated. Consequently, using these technologies can help us reach new conclusions about the psychological effect of space design.

## Method

The method was structured in two phases. Both phases were oriented toward studying the effect that different environmental satisfaction sources in paediatric waiting rooms have on companions' stress. This division allowed to limit the number of sources to be analysed: in the first phase, the sources with greater effect in reducing stress were identified in physical waiting rooms; and in the second phase, these sources were analysed in an isolated and combined way under controlled laboratory conditions. Table 1 shows the most relevant features.

The general characteristics of the two phases are as follows.

In Phase I, we identified the environmental satisfaction sources in paediatric waiting rooms that have the greatest effect on companions' stress reduction. This was done by reviewing the relevant literature, which resulted in 19 sources. The field study was carried out *in situ*, given that context could affect the responses. In this phase, 120 children's companions assessed the effect of 19 environmental satisfaction sources (see Figure 4) on stress in 20 paediatric waiting rooms located in Spain. These waiting rooms were located in the Valencian Community, a Mediterranean region located in the southeast of Spain with approximately 5 million inhabitants. In this region, we selected representative waiting rooms of municipalities with more than 50,000 inhabitants, using the technique of reduction of the affinity diagram. The number of 20 waiting rooms offered a sample that the research team considered sufficiently representative and differentiated of waiting room designs. A stress self-assessment was also used to ensure that the participants were in a highly stressful situation when they assessed sources. Our results show the environmental satisfaction sources with the greatest effect on stress reduction for the context studied.

In Phase II, we identified the combination of environmental satisfaction sources (CESS) identified during Phase I that had the greatest effect on stress reduction. The field study was carried out in a laboratory, using immersive virtual reality systems. In this study, 26 children's companions were exposed to four different CESS in a virtual waiting room, and psychological and neurophysiological responses related to stress were observed. Simulations were validated through the participants' sense of presence, measured through

**Table 1.** Most relevant features of the general methodology.

| Phase and objective | Material and method | Analysis | Anticipated result |
|---|---|---|---|
| Phase I<br>Identify the environmental satisfaction sources of the waiting rooms which have a higher incidence on the companion's stress reduction | Field study: *in situ*<br>N: 120 fathers/mothers<br>Stimuli: 20 waiting rooms<br>Material: questionnaire<br>Dependent variables: 'contribution to stress reduction' y 'perceived stress' | Phase I: Analysis of the individual effects of the environmental satisfaction sources on stress reduction | Inventory of the environmental satisfaction sources which have a higher incidence on stress reduction |
| Phase II<br>Identify how the CESS (combinations of environmental satisfaction sources) of the waiting rooms influence the companion's stress reduction | Field study: environmental simulation in a laboratory<br>N: 26 fathers/mothers of children<br>Stimuli: four environmental simulations de waiting rooms, each one with a different CESS based on the results of Phase I<br>Material: presence and stress questionnaires, and neurophysiological acquisition devices<br>Dependent variables: psychological ('level of presence', and 'perceived stress'); and neurophysiological (registers of 'EDA', 'HRV', and 'EEG') | Phase IIA: Analysis of levels of presence in CESS simulations<br>Phase IIB: Analysis of psychological stress metrics and their relationships<br>Phase IIC: Analysis of neurophysiological metrics related to stress<br>Phase IID: Relationship between neurophysiological and psychological metrics | Inventory of the contributions of stress reduction (at psychological and neurophysiological levels) of different CESS |

psychological responses (Phase IIA). Subsequently, psychological and neurophysiological responses were obtained to analyse participants' stress levels. For psychological responses, stress self-assessments were used. For neurophysiological responses, the metrics of EDA, HRV and EEG were used. The results show the effect of CESS on stress reduction at the psychological (Phase IIB) and neurophysiological (Phase IIC) levels and the relationship between their metrics (Phase IID).

## Materials and methods

This section describes the materials and methods used in Phase I and Phase II.

### *Phase I*

Phase I focused on identifying the environmental satisfaction sources with the greatest effect on stress reduction. A sample of participants in a real waiting situation in physical waiting rooms completed a questionnaire on the impact of different sources of environmental satisfaction on stress. The questionnaire also assessed their state of stress.

#### *Participants*

Participants were 120 fathers or mothers of children who are users of a paediatric service. The sample was gender balanced (60 women and 60 men), and the average age was 37 years ($\sigma = 6.77$). The selection was based on the criterion that companions be within the first degree of consanguinity, the most common children's companion profile.

#### *Stimuli*

The stimuli were applied in 20 paediatric service waiting rooms in various healthcare institutions (both in hospitals and in community health centres). We tried to compile a varied set, given the 'nesting' limitation that can arise when working with real stimuli (Kish, 1995). Each room was assessed *in situ* by six participants (three men and three women).

#### *Questionnaire*

Two types of questions were asked of each participant:

- Assessment of the stress level in each waiting room with the question 'At this moment, I feel a stress level … ' followed by a Likert scale ranging from −2 to 2 in increments of half points.
- Assessment of the contribution of 19 environmental satisfaction sources that are characteristic of waiting room spaces in general in terms of their effect on stress reduction. The selection of these sources was carried out by the work group (consisting of two members of the research team, two external architects, two fathers and two mothers of children who use a paediatric service), taking into consideration the bibliography and previous visits to the 20 waiting rooms considered in the study. The environmental satisfaction sources were 'space for baby buggies', 'furniture arranged facing one another', 'furniture arranged in groups', 'silence', 'sounds of nature', 'adjustable lighting in each section of the waiting room', 'furniture arranged not facing one another', 'space for companions', 'non-intense lighting', 'appropriate signage', 'adjustable temperature in each section of the waiting room', 'nature pictures', 'natural lighting', 'vending

machine', 'nice scent', 'pictures for children', 'non-intense music', 'vegetation' and 'play facilities for children'. The assessment was performed using the question 'For the waiting rooms of the paediatric service in general, this source contributes to reducing stress … ' followed by a scale ranging from 0 to 10.

The participants completed the questionnaire during their waits in the stimuli rooms. They all waited for between 15 and 30 min to mitigate possible differences, given that this is an important factor in these experiences (Magaret, Clark, Warden, Magnusson, & Hedges, 2002).

### Data analysis

After the database had been compiled and anonymized, the statistical analysis was carried out. The average of each environmental satisfaction source was obtained to identify the sources that have the greatest effect on stress reduction. IBM SPSS software was used (v.17.0; www.ibm.com/products/spss-statistics).

## Phase II

Phase II focused on identifying how a combination of CESS has an influence. For that purpose, participants in a stressful situation (generated by means of a psychological stressor) were exposed to different CESS in a waiting room through environmental simulation set-ups, and psychological and neurophysiological metrics of the stress levels were recorded. All participants visualized a training scenario for a few minutes before starting the experiences to improve their adaptation to the virtual reality set-up. Figure 1 shows the general sequence.

### Participants

Participants were 26 fathers or mothers of children in the paediatric service. The data for two participants were removed because of neurophysiological acquisition problems in one case and the exclusion criteria described below in the other. The final sample (24) was gender balanced (54% male and 46% female), and the average age was 37 years ($\sigma = 3.99$).

There were three selection criteria: children should be users of the paediatric service, should not suffer from any condition with contraindications for the use of virtual reality technologies, and should have normal or corrected-to-normal vision with contact lenses.

### Psychological stressor

Before experiencing the CESS, the participants were exposed to a psychological stressor. This consisted of the performance of arithmetic tasks, for 120 s, based on the Montreal Imaging Stress Task (Dedovic, Renwick, Mahani, & Engert, 2005) and adapted for difficulty for each subject by means of a previous task.

With the aim of verifying stress generation, the interviewer asked the participants to self-assess their stress levels using a Likert-type scale ranging from −2 to 2. All participants reported high stress levels ($X = 1.41$, $S = 0.590$), so the stressor was considered appropriate. Although the stress generated by this method may differ from the experiences that the experiment is designed to simulate, it is an appropriate approximation in laboratory conditions (Moya-Albiol & Salvador, 2001).

### CESS configurations

The base stimulus was always the same (a visual, auditory and olfactory replica of the real waiting room that was considered standard). On this base stimulus, three different CESS were implemented. The choice of environmental satisfaction sources was based on the results of Phase I ('nice scent', 'pictures for children', 'non-intense music', 'vegetation' and 'play facilities for children') in order not to make the combinations so complicated as to be impracticable. The play facility for children was fixed as a constant because it is common in Spain, and the other four were grouped according to their affinity described by Harris et al. (2002) with 'interior design features' (vegetation and pictures for children) and 'ambient environment features' (non-intense music and a nice scent). Specifically, the composition *Miserere mei, Deus* by Gregorio Allegri (Thoma et al., 2013) and the scent of lavender (Fenko & Loock, 2014) were chosen because they were evaluated as relaxing. In this way, four CESS configurations were developed. Table 2 specifies each CESS configuration, according to the sensory modalities. All the participants were exposed to the four configurations, following an incomplete counterbalancing design.

### Environmental simulation set-ups

The CESS experiences were carried out by means of visual, auditory and olfactory environmental simulations. The following devices were used:

- HTC Vive. Visual stimulation. An HMD developed by HTC and Valve (www.vive.com). This displays $2160 \times 1200$ pixels ($1080 \times 1200$ per eye) with a field of view of 110 degrees and a 90 Hz refresh rate.

| | CONCEPT | TIME (MINUTES) | |
|---|---|---|---|
| Pre-experiences | **BEGINNING WITH THE PARTICIPANT**<br>Reception, basic instructions, signature of the consent, demographical questionnaire, adaptation to virtual reality set-up, and placement of neurophysiological acquisition devices.<br>Recorded data: psychological data related to stress (metric: Trait Anxiety Inventory) | ≈10 | ↓ |
| | **BASE LINE**<br>Open Eyes + Closed Eyes<br>Recorded data: neurophysiological data retated to stress (base-line metrics: EDA-Phasic, EEG-Highbeta, EEG-AAPEn) | 4 (2+2) | |
| | **STRESSOR SETTING TASK**<br>Arithmetical task to adjust the difficulty of the stressor | 1 | |
| | **INSTRUCTIONS**<br>*"Now you are going to listen to a recording and carry out a task. Then, you will be immersed in a space. Imagine that it is a waiting room in the paediatric service. You are waiting for your turn with your child, who you are accompanying for a checkup of certain importance.Wait sitting.After that, answer some questions about how you feel. There are no correct or incorrect answers. Don't spend too much time, but give the answer that best describes yourself. This will be repeated 4 times.* | ≈2 | |
| CESS-experiences (repited for each CESS) | **PREPARATION AUDIO**<br>Preparation relaxing audio before the stressor task (to avoid excesive fatigue with the repetition of the sequence)<br>During this period the room is ventilated to avoid accumulation of smells | 2 | ↓ CESS#1⟶CESS#2⟶CESS#3⟶CESS#4 (counterbalanced) |
| | **STRESSOR**<br>Arithmetic tasks. | 2 | |
| | **STRESSOR VERIFICATION**<br>Recorded data: psychological data related to stress (metric: stress self-assessment) | ≈0.5 | |
| | **EXPERIENCE OF THE CESS**<br>Environmental simulation of the assigned CESS<br>(the interviewer adjusted the virtual reality technologies)<br>Recorded data: neurophysiological data related to stress (metrics: EDA-Phasic, HRV-LFHF, EEG-Highbeta, EEG-AAPEn) | 2 | |
| | **ASSESSMENT OF THE EXPERIENCE**<br>Recorded data: psychological data related to stress (stress self-assessment, and State Anxiety Inventory), and psychological data related to presence (SUS questionnaire) | ≈5 | |
| Post-experiences | **ENDING WITH THE PARTICIPANT**<br>Removal of the devices, accompaniment to the exit. | ≈5 | ↓ |
| | **TOTAL** | ≈67 | |

**Figure 1.** General sequence of Phase II.

Figure 2 shows both types of CESS configurations (CESS#1 and CESS#2; CESS#3 and CESS#4) at the visual stimulation level.

- HD 558. Auditory stimulation. Headphones developed by Sennheiser (www.en-us.sennheiser.com). Two types of CESS configurations were reproduced at the auditory level: CESS#1 and CESS#3, a binaural recording of the ambient noise in a paediatric waiting room; and CESS#2 and CESS#4, the simulation of a loudspeaker system broadcasting *Miserere mei, Deus*.
- Scentpalette. Olfactory stimulation. Aromatizing device developed by Head Hunter 2000 (www.scentpalette.com). Two types of CESS configurations were spread at the olfactory level: CESS#1 and CESS#3, a hospital smell (modification of a eucalyptus and bleach base), and CESS#2 and CESS#4, a lavender scent.

**Table 2.** CESS configurations, according to the involved sensory modalities.

| | Sensory modality | | | | | |
|---|---|---|---|---|---|---|
| | Visual | | Auditory | | Olfactory | |
| CESS | Standard waiting room replica | Vegetation, and pictures for children | Standard hospital ambient noise | Relaxing and non-intense music | Standard hospital simulation scent | Nice relaxing scent |
| CESS#1 | X | | X | | X | |
| CESS#2 | X | X | X | | X | |
| CESS#3 | X | | X | X | X | X |
| CESS#4 | X | X | X | X | X | X |

Figure 3 shows one of the experiences.

## Data processing

Psychological and neurophysiological data were recorded for each participant. iMotions (v.6.1; www.imotions.com) was used on the research PC to manage the protocol and compile the data.

Psychological data. These data were focused on measuring the participants' stress and sense of presence evoked by the experiences of the CESS. For stress metrics, a stress self-assessment and the State-Trait Anxiety Inventory were used, and, for sense of presence, a SUS questionnaire was used.

- Stress self-assessment. Assessment of stress by means of a Likert scale ranging from −2 to 2. The question 'This waiting room has caused me stress … ' was used.
- State-Trait Anxiety Inventory. Test that assesses anxiety as a trait and as a state, developed by Spielberger, Gorsuch, and Lushene (1970). It consists of two inventories, one for each concept (Trait Anxiety Inventory and State Anxiety Inventory). Both contain 20 items evaluated by means of a Likert scale ranging from 1 to 4, with the outcomes being transformed into percentiles. Using the Trait Anxiety Inventory, participants under and over the 25th and 75th percentiles were excluded (one was removed) to avoid possible anomalies (Maxfield & Melnyk, 2000).
- SUS questionnaire. Presence test developed by Slater, Usoh, and Steed (1994). This measures the level of presence through six items on a Likert scale ranging from 1 to 7. This assessed whether the simulations could be considered satisfactory.

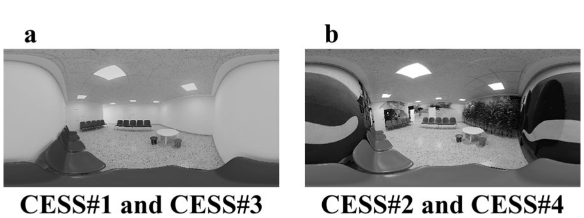



**Figure 2.** CESS configurations at visual level stimulation.

Neurophysiological data. These data were used to complement the psychological data. EDA, HRV and EEG metrics related to stress were used.

- EDA. Analysing this signal reveals its phasic component, an indicator of sympathetic activity. The EDA signal was recorded at 128 Hz using a Shimmer 3GSR+ device (www.shimmersensing.com). The raw signal was pre-processed and analysed using Ledalab (v.3.4.8, www.ledalab.de) via Matlab (v.2016a; www.mathworks.com). Pre-processing consisted of (1) Butterworth low-pass signal filtering at 2.5 Hz (Valenza & Scilingo, 2014), (2) signal downsampling to 10 Hz (Lang, Zhou, Schwartz, Bolls, & Potter, 2000) and (3) visual-diagnostic of artefacts and their corrections. The continuous decomposition analysis method was used to calculate the phasic metric (Benedek & Kaernbach, 2010). Thereafter, the values were standardized following Venables and Christie (1980).
- HRV. Analysing this signal in the frequency domain makes it possible to distinguish the ratio between low frequency to high frequency (LF/HF). This ratio is a balance indicator of sympathetic activity over parasympathetic activity (Malliani, 1999). The electrocardiogram signal was recorded at 256 Hz using a b-Alert x10 device (www.advancedbrainmonitoring.com). It was pre-processed and analysed using HRVAS (v.2014-03-21) via Matlab. Pre-processing consisted of (1) detection of R-points by means of the Pan-Tompkins algorithm (Pan & Tompkins, 1985) and (2) visual diagnosis of ectopic beats and their corrections and the elimination of excessively noisy intervals. The analysis processed the interbeat intervals in the time–frequency domain using the Welch method and setting the frequencies of 0.05–0.15 Hz for LF and 0.15–0.4 Hz for HF (Berntson et al., 1997).
- EEG. In order to analyse this signal, the power spectral density classification within defined frequency bands is often used. More recently, analyses of irregularity have been proposed as appropriate. Thus, the metrics used in this study were the relative power of

**Figure 3.** Participant of Phase II, during the CESS#2 experience.

the highbeta band (21–30 Hz) of the C3 electrode (Choi, Kim, & Chun, 2015) and amplitude-aware permutation entropy (AAPEn of the P3 electrode; Azami & Escudero, 2016). The EEG signal was recorded at 256 Hz using a b-Alert x10 device. The raw signal was pre-processed and analysed using EEGLAB (Delorme & Makeig, 2004) via Matlab (v.2016a). The pre-processing consisted of the signal conditioning stages and artefact identification. Signal conditioning consisted of (1) EEG traces baseline removal by mean subtraction, (2) band pass filtering between 0.5 and 40 Hz (Gudmundsson, Runarsson, Sigurdsson, Eiriksdottir, & Johnsen, 2007) and (3) checking corrupted data channels, which were considered thus if the signal was flat more than 10% of the total duration or if the channel kurtosis reached a threshold of 5 standard deviations from all-channels kurtosis (Delorme, Makeig, & Sejnowski, 2001). Where there was a corrupted electrode, the data were interpolated using the neighbouring electrodes, but where more than one was corrupted, the complete record was deleted (Colomer et al., 2016). Following this, the resultant signal was divided into one-second epochs. Artefact identification involved (1) checking corrupted epochs, which were considering thus if kurtosis reached the same threshold within a single channel, (2) automated detection, rejecting epochs exceeding the threshold of 100µV or a gradient of 70.00 µV between samples, and (3) independent component analysis (ICA) application (Hyvärinen & Oja, 2000), rejecting those related to an artefact. Finally, the selected metrics were calculated from the resultant signals.

The neurophysiological data were recorded at two times (Figure 1): during the baseline of the 'pre-experience' stage (4 min) and during the experience of each CESS of the 'CESS-experience' stage (2 min per CESS). The baseline was incorporated because the correlation of some neurophysiological metrics (EDA-Phasic, EEG-Hightbeta and EEG-AAPEn) was calculated using the normalized values with regard to the baseline ($M_n = (M_{CEES} - \bar{M}_{BASELINE}) / SD_{BASELINE}$). In doing so, two outcomes were obtained: (1) the average of each CESS and (2) the analysis as a function of time, assigning to each second its relative value with regard to the initial second of each CESS ($M_{rnTn} = M_{nTn} / M_{nT0}$) and, for the representation, normalizing it from 0 to 1 considering the values of all CESS.

### Data analysis

After the database of participants' psychological and neurophysiological responses had been collected and anonymized, statistical analysis consisting of four subphases was carried out. IBM SPSS software was used.

- Phase IIA: Analysis of levels of presence in CESS simulations. The average sense of presence was analysed for each environmental simulation. We verified that this level was sufficient.
- Phase IIB: Analysis of stress psychological metrics and their relationships. First, the average levels of stress self-assessment and the State Anxiety Inventory for each CESS simulation were obtained. Next, the Friedman test and post hoc analysis with Wilcoxon signed-rank tests were conducted to identify any statistically significant differences between each pair of simulations. The Friedman test was used because the analysis was based on repeated measures comparisons, and the variables were not normally distributed, as per the results of the Kolmogorov–Smirnov test ($p < 0.005$). Finally, the Spearman correlation coefficient between psychological metrics was used to examine possible relationships between the two psychological metrics.
- Phase IIC: Analysis of neurophysiological metrics related to stress. As in Phase IIB, the average levels of neurophysiological metrics related to stress for each CESS simulation were first obtained. Next, the Friedman test and post hoc analysis with Wilcoxon

signed-rank tests were conducted. The analysis of these metrics was complemented with a descriptive analysis as a function of time so that it was possible to graphically observe changes in the levels of stress due to the experience of the CESS over time.

- Phase IID: Relationship between the neurophysiological and psychological metrics. The Spearman non-parametric correlation coefficient was used to examine possible relationships between the psychological and neurophysiological responses.

## Results

### Phase I

Statistical analysis of the Phase I data produced the following results.

#### Analysis of the individual effects of the environmental satisfaction sources on stress reduction

Participants' assessments of the 19 environmental satisfaction sources according to their effects on stress reduction were obtained (Figure 4). Five of these sources ('nice scent', 'pictures for children', 'non-intense music', 'vegetation' and 'play facilities for children') had relatively high values with respect to the others. Conversely, two sources ('space for baby buggies' and 'furniture arranged facing one another') had relatively low values. These results show the varying effects of environmental satisfaction sources on reducing the stress of fathers and mothers of child users of waiting rooms. Although the findings from this phase cannot be used as a guide for the stimuli, they suggest the directions in which efforts should be made to incorporate environmental satisfaction sources into paediatric waiting rooms. All participants reported high stress levels ($X = 1.03$, $S = 0.978$) while they were waiting to be seen. This result indicates that they were in a highly stressful situation when they assessed the environmental satisfaction sources.

### Phase II

Statistical analysis of the Phase II data produced the following results.

#### Phase IIA: analysis of sense of presence in CESS simulations

Average levels of sense of presence per participant (according to the SUS questionnaire) for each CESS simulation were obtained (Figure 5). They were considered to be sufficient, taking into account the results obtained by studies using similar technologies (Slater & Steed, 2000). Thus, the simulations can be considered satisfactory.

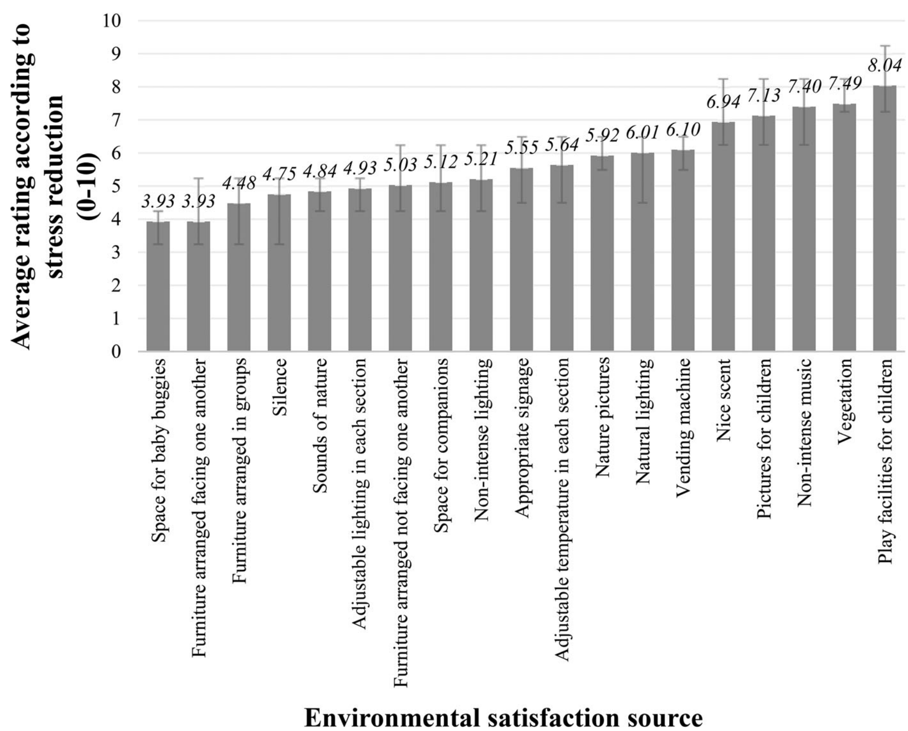



**Figure 4.** Average stress reduction ratings for the environmental satisfaction sources.

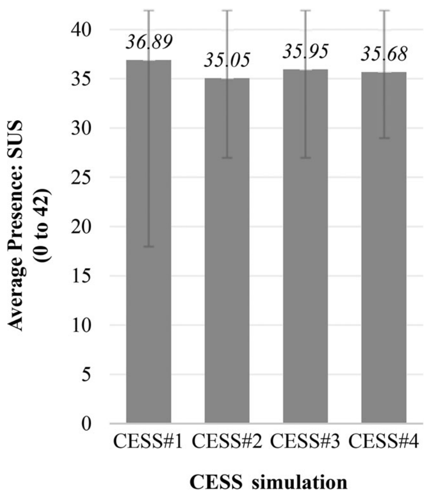



**Figure 5.** Average level of presence per participant in each CESS simulation.

### *Phase IIB: analysis of psychological stress metrics and their relationships*

Psychological stress was measured by means of stress self-assessment and the State Anxiety Inventory. Average levels of both metrics for each CESS simulation were obtained, and significant differences were examined.

*Stress self-assessment.* We observe that all CESS achieve stress reduction with respect to the stress for CESS#1 (standard waiting room). CESS#3 achieves a greater reduction than CESS#2, and their combination (CESS#4) has a synergistic effect. The Friedman test indicates significant differences for the set of analysed CESS ($p = 0.000$). Post hoc analysis with Wilcoxon signed-rank tests shows that significant differences exist between all combinations except between CESS#1 and CESS#2 ($p = 0.096$; Figure 6(a)).

*State Anxiety Inventory.* Similar stress reduction to that quantified by the stress self-assessment is observed, even though the stress reduction for CESS#4 is less pronounced than for the others. The Friedman test shows significant differences for the set of analysed CESS ($p = 0.000$). Wilcoxon signed-rank tests show that differences exist between all combinations (Figure 6(b)).

Finally, bivariate correlations were obtained between both metrics using the Spearman coefficient. This analysis shows that the two metrics are significantly related (Spearman correlation coefficient = 0.493, significance level = 0.000). Therefore, in this study, it can be argued that stress self-assessment, although less exhaustive, provides insight when quantifying the level of psychological stress.

### *Phase IIC: analysis of neurophysiological metrics related to stress*

Neurophysiological stress was measured by means of EDA-Phasic, HRV-LFHF, EEG-Highbeta and EEG-AAPEn metrics. The levels for each CESS simulation were obtained, and significant differences were examined. In addition, analysis as a function of time was performed.

*EDA-Phasic.* We observe that all CESS achieve a reduction in stress with respect to stress levels for CESS#1 (standard waiting room). Although this does

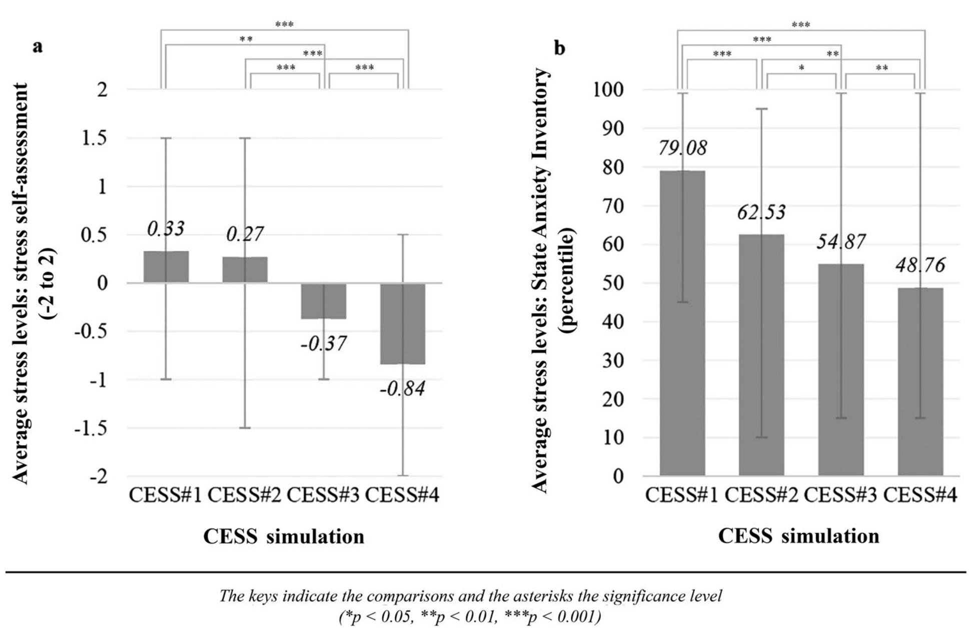



**Figure 6.** Average level of psychological stress per participant in each CESS simulation.

not follow the same pattern as at the psychological level, because CESS#3 has a slightly higher average value than CESS#2, the synergistic effect of CESS#4 also appears in this metric. The Friedman test shows significant differences for the set of analysed CESS ($p = 0.001$). Wilcoxon signed-rank tests show that differences exist between all the CESS except between CESS#2 and CESS#3 ($p =$ 1.000) and between CESS#3 and CESS#4 ($p = 0.096$; Figure 7(a)). Figure 7(b) shows the changes in this metric as a function of time. Although all CESS reduce stress levels with respect to the base position, CESS#3 and CESS#4 do so significantly quicker. It is also notable that all the CESS representations as a function of time are interrupted at approximately second 90.

*HRV-LFHF.* All CESS achieve a stress reduction with respect to the stress levels for CESS#1 (standard waiting room), and CESS#4 has a synergistic effect. However, CESS#2 and CESS#3 have similar values. The Friedman test indicates that there are no significant differences for the set of analysed CESS ($p = 0.494$). A more specific analysis by means of Wilcoxon signed-rank tests shows that there are indeed no significant differences among the CESS, except between CESS#1 and CESS#4 ($p =$ 0.003) and between CESS#1 and CESS#3 ($p = 0.035$; Figure 8(a)). Figure 8(b) shows the changes in this metric as a function of time. A notable difference is found between CESS#1 and the other CESS: This CESS does not manage to reduce stress levels from second 30 onwards, but the other configurations continue to contribute to reducing stress levels until second 60. The CESS#1 and CESS#3 representations as a function of time are interrupted at approximately second 90, similar to the previous metric.

*EEG-Highbeta.* This metric shows slightly different behaviour to the others. Thus, all CESS, except CESS#2, achieve stress reduction when compared to CESS#1 (standard waiting room), and the contribution of CESS#3 to reducing stress is minor. Nevertheless, the synergistic effect of CESS#4 coincides with the previous metrics. The Friedman test indicates significant differences for the set of analysed CESS ($p = 0.000$). Wilcoxon signed-rank tests show these differences between CESS#1 and CESS#2 ($p = 0.000$) and between CESS#2 and CESS#4 ($p = 0.000$; Figure 9(a)). Figure 9(b) shows the changes in this metric as a function of time. Although CESS#2 has average values that are higher than those of CESS#1, CESS#2 has a greater reduction in the final period. Perhaps a more prolonged exposure to the configurations would improve its overall values. Furthermore, the strong similarity between the patterns of CESS#1 and CESS#2 reveals that the environmental satisfaction sources of CESS#3 might function in a different way. The CESS#1 representations as a function of time are also interrupted at approximately second 90.

*EEG-AAPEn.* All CESS achieve stress reduction with respect to the stress levels for CESS#1 (standard waiting room), and CESS#4 has a synergistic effect. However, the reduction in CESS#2 is marginal, with an average value that is very similar to the value for CESS#1. The

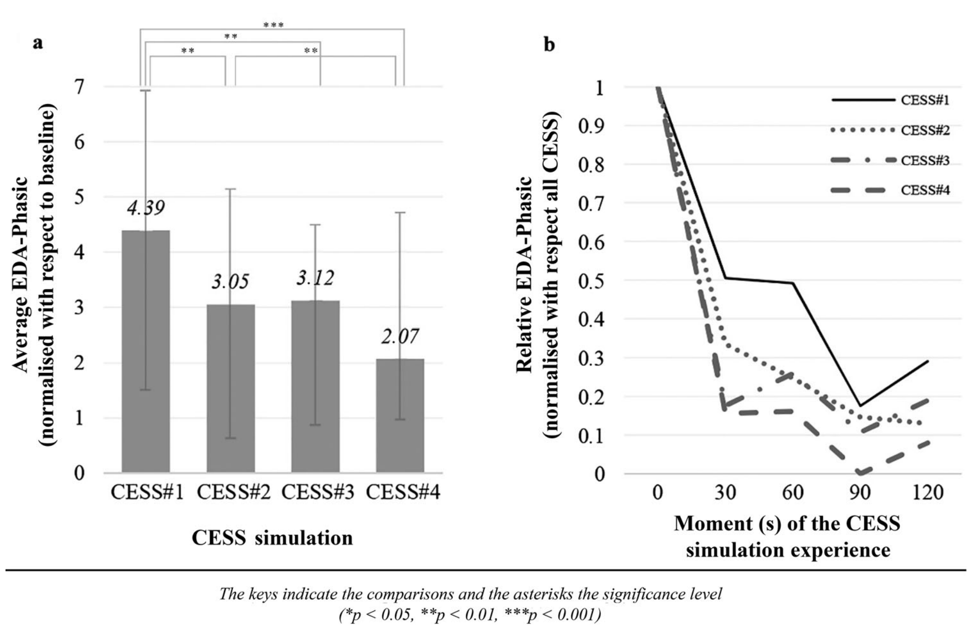



**Figure 7.** Average EDA-Phasic per participant in each CESS simulation.

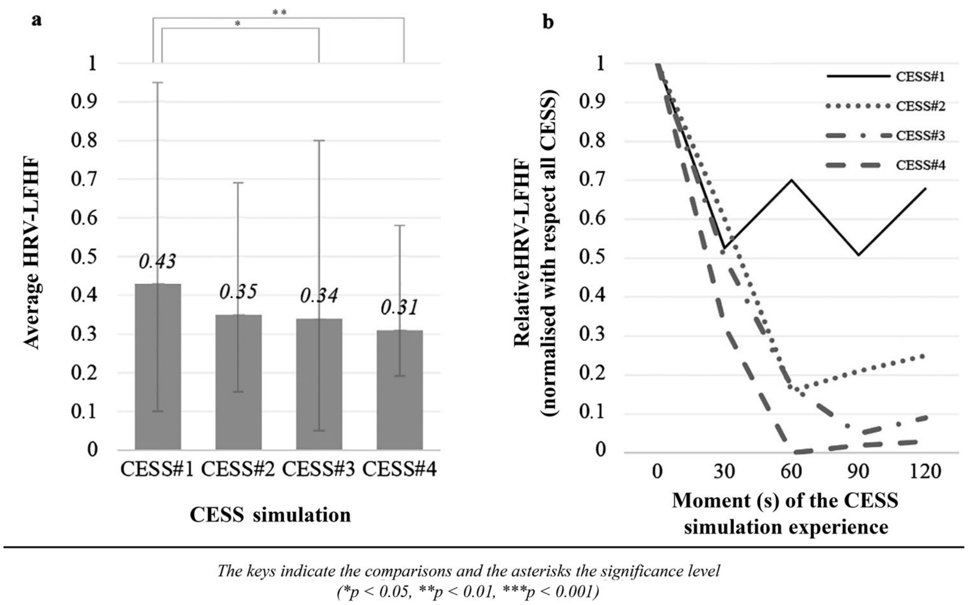



**Figure 8.** Average HRV-LFHF per participant in each CESS simulation.

Friedman test shows significant differences for the set of analysed CESS ($p = 0.005$). Wilcoxon signed-rank tests show that these differences exist between CESS#1 and CESS#3 ($p = 0.007$), CESS#1 and CESS#4 ($p = 0.000$), CESS#2 and CESS#3 ($p = 0.010$) and CESS#2 and CESS#4 ($p = 0.001$; Figure 10(a)). Figure 10(b) shows the changes in this metric as a function of time. CESS#3 and CESS#4, although different in their average values, follow a constant tendency in the reduction of stress levels (in contrast to CESS#1 and CESS#2, which experience greater disruptions). All CESS except CESS#2 are interrupted at approximately second 90.

### *Phase IID: relationship between neurophysiological and psychological metrics*

Bivariate correlations between the neurophysiological and psychological metrics were obtained. The Spearman non-parametric correlation coefficient was used with a significance level of $p < 0.05$. Analysis shows stronger correlations between the stress self-assessment and the neurophysiological metrics. Thus, EDA-Phasic, EEG-Highbeta, and EEG-AAPEn metrics have a significant positive correlation with the psychological metric, which, in the case of the last EEG metric, is also applicable to the State Anxiety Inventory. There is no

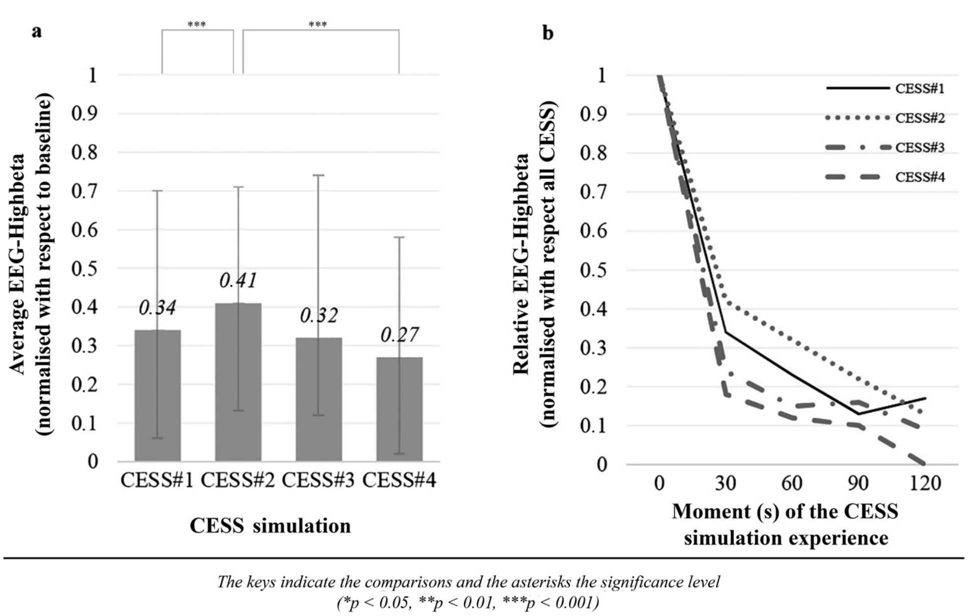
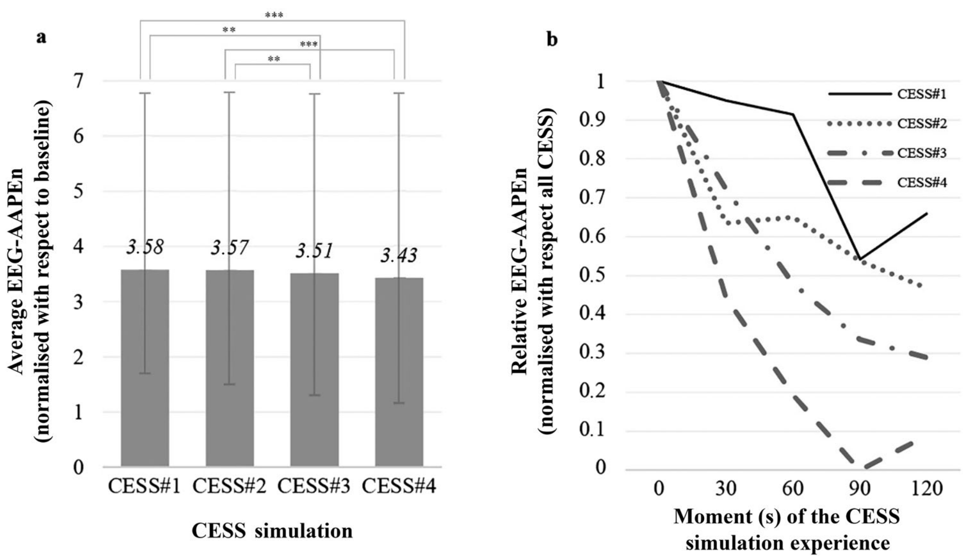



**Figure 9.** Average EEG-Highbeta per participant in each CESS simulation.




*The keys indicate the comparisons and the asterisks the significance level (*p < 0.05, **p < 0.01, ***p < 0.001)*

**Figure 10.** Average EEG-AAPEn per participant in each CESS simulation.

**Table 3.** Correlations between the neurophysiological and psychological metrics.

| | | Stress self-assessment | State Anxiety Inventory |
|---|---|---|---|
| EDA-Phasic | Spearman correlation coefficient | .547** | .034 |
| | Significance level | .000 | .790 |
| HRV-LFHF | Spearman correlation coefficient | −.056 | −.047 |
| | Significance level | .405 | .481 |
| EEG-Highbeta | Spearman correlation coefficient | .229* | .102 |
| | Significance level | .002 | .175 |
| EEG-AAPEn | Spearman correlation coefficient | .479** | .316** |
| | Significance level | .000 | .000 |

correlation between HRV-LFHF and psychological metrics. Table 3 shows the results.

## Discussion

The contributions of this study relate to three areas: methodology, application and metrics to quantify stress.

At the methodological level, there are two main contributions. First, combinations of environmental satisfaction sources were studied. Although many studies tackle the improvement in the condition of patients based on specific variables, this study provides insight into their combined effect. Second, neurophysiological measures were used to quantify stress. This allowed us to explore factors related to unconscious processes.

At the application level, our findings have two important implications: (1) stress reduction in children's companions and (2) the effect of environmental satisfaction sources based on sensory modality.

With regard to stress reduction, we suggest that it is possible to use environmental satisfaction sources to reduce the stress levels of children's companions. This result is in line with those reported by Ulrich (1991) and Kjellgren and Buhrkall (2010). We show that, with respect to the stress of the standard waiting room, stress reduction due to all combinations of environmental satisfaction sources is evident at the psychological and neurophysiological levels. The EEG-Highbeta metric offers the only contradictory result, which even differs from the other EEG metric (AAPEn). The effect of environmental satisfaction sources on stress reduction is different depending on their sensory modality. The greatest effect is achieved through the combination of visual, auditory and olfactory sources (CESS#4), with high synergy at the psychological and neurophysiological levels. The importance of this result is that no similar experiment has been carried out previously. At the level of specific stimuli, the selected ambient environment features (CESS#3) produce a greater effect than the interior design features (CESS#2), especially on a psychological level. This result is interesting because hospitals generally focus on visual environmental satisfaction sources (Nanda et al., 2012), ignoring other stimuli that can significantly reduce stress.

At the level of use of the psychological and neurophysiological metrics, three aspects should be discussed: (1) the choice of psychological metrics, (2) the choice of neurophysiological metrics and (3) the interruption of the representations of the metrics as a function of time.

As to the choice of psychological metrics, stress self-assessment may have advantages. It strongly correlates with the State Anxiety Inventory, and, contrary to this metric, correlates with most neurophysiological metrics. Despite being less exhaustive than the inventories developed for stress assessment (Tennant & Andrews, 1976), the stress self-assessment is faster to administer. This is advantageous if the experimental phase is prolonged or HMD devices are used, because its resolution makes it difficult to read. Consequently, stress self-assessment is a tool that should be considered in studies that follow a similar methodology.

As to the neurophysiological metrics, all seem appropriate, with the exception of HRV-LFHF. This is the only neurophysiological metric that does not correlate with either of the two psychological metrics. This result supports other studies showing that HRV-LFHF is insufficient to measure the sympathovagal balance (Billman, 2013). Conversely, EEG-AAPEn correlates more strongly with the two psychological metrics than the other neurophysiological metrics. It should be noted that EEG-AAPEn has been identified as a powerful tool for the identification of stress by means of EEG (García-Martínez, Martínez-Rodrigo, Zangróniz, Pastor, & Alcaraz, 2017). The correlations of EDA-Phasic and EEG-Highbeta with stress are in line with the classic literature. Moreover, neurophysiological metrics enable analysis as a function of time. It has been found that auditory and olfactory environmental satisfaction sources reduce stress levels quicker than visual sources; this finding is consistent with studies that discuss their potential (Diego et al., 1998). In general, neurophysiological metrics confirm their validity for quantifying stress in virtual simulations. However, this study only considers a selection of neurophysiological metrics that were deemed appropriate based on the literature review. Future research could benefit from adding others that have also been linked to stress – such as the SD/rMSSD ratio in HRV (Sollers, Buchanan, Mowrer, Hill, & Thayer, 2007) and the nSRR in EDA (Blechert, Lajtman, Michael, Margraf, & Wilhelm, 2006) – as well as neurophysiological records of a different nature – such as pupillometry (Pedrotti et al., 2014). Adding these metrics could provide a more exhaustive study.

In terms of the disruption of the tendency in the neurophysiological metrics, it is hypothesized that this is due to the fatigue effect generated by the technology employed. This occurs with all neurophysiological metrics around second 60 for HRV-LFHF and second 90 for the others. Virtual reality may provoke different symptoms and effects, among which is an increase in arousal (Cobb, Nichols, Ramsey, & Wilson, 1999). This effect may increase depending on the device employed, such as HMDs. Moreover, studies using similar set-ups have found comparable effects, although these effects were not specified in terms of time (Felnhofer et al., 2015). Thus, because there seems to be a notable negative effect after 90 seconds, exceeding this point may not be appropriate given the objective of the study. This effect could have conditioned the stress levels, but the period of adaptation to the virtual reality set-up and the counterbalancing design of the CESS experiences would have minimized the effects of the experience of the experiment for comparison purposes. Specific studies should be carried out in the future to evaluate this effect in detail, although it is likely to disappear as environmental simulation technologies improve.

Some limitations of the study must be taken into account, particularly when extrapolating the results to other contexts. First, the results are focused on a paediatric service waiting room, and the participants were companions. It is possible that the results may vary as a consequence of repeating the study in a different space and with different participant profiles. In terms of space, the environmental satisfaction sources should be adapted to the different health centre services. Regarding participant profiles, divergences may exist because of different origins of stress in staff (Gray-Toft & Anderson, 1981) and patients (Jessee, Wilson, & Morgan, 2000). Thus, future studies could consider all profiles to establish common strategies within the same service. Second, the waiting room that was used as the standard is representative of Spanish waiting rooms, with the same colours, smells and sounds. It is possible that the results would differ if the research was repeated in another country. Thus, in order to recreate this study, different samples and locations should be used.

## Conclusions

This research examines the effect that certain paediatric service waiting room configurations have on companions' stress levels. The results suggest that a combination of multisensory environmental satisfaction sources produce a synergistic effect measurable at the psychological and neurophysiological levels. By studying them in terms of sensory modality, we observe that there is greater stress reduction through auditory and olfactory means than through visual means. Our methodological contribution is twofold: (1) simultaneous measurement of the participants' psychometric and neurophysiological responses and (2) analysis of the environmental satisfaction sources both in an isolated and combined way. The conclusions of this study may be of interest for a wide audience, including virtual reality scholars and professionals involved in the design and management of health centres. For research that focuses on or uses virtual reality as a tool, this study indicates that there may be a period (of 60–90 s) after which, with the technology used, an increase in arousal is generated. This may be a limitation in certain studies. For design and management, particularly of the paediatric service, this study offers findings that may be useful. In terms of design and construction, this study offers strategies to address the design of these spaces, and, in terms of management, the study provides empirical evidence of the importance of certain actions to reduce the stress levels of the users of these services. In short, this study can be useful for professionals seeking to study or reduce the stress levels of health centre users as well as those who use similar tools for other purposes.

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## References

Andrade, C. C., & Devlin, A. S. (2015). Stress reduction in the hospital room: Applying Ulrich's theory of supportive design. *Journal of Environmental Psychology*, *41*, 125–134.

Andrade, C. C., Devlin, A. S., Pereira, C. R., & Lima, M. L. (2017). Do the hospital rooms make a difference for patients' stress? A multilevel analysis of the role of perceived control, positive distraction, and social support. *Journal of Environmental Psychology*, *53*, 63–72.

Arneill, A. B., & Devlin, A. S. (2002). Perceived quality of care: The influence of the waiting room environment. *Journal of Environmental Psychology*, *22*(4), 345–360.

Avrahami, D. (2006). Visual Art therapy's Unique contribution in the Treatment of post-Traumatic stress Disorders. *Journal of Trauma & Dissociation*, *6*(4), 5–38.

Azami, H., & Escudero, J. (2016). Amplitude-aware permutation entropy: Illustration in spike detection and signal segmentation. *Computer Methods and Programs in Biomedicine*, *128*, 40–51.

Baker, J., & Cameron, M. (1996). The effects of the service environment on affect and consumer perception of waiting time: An integrative review and research propositions. *Journal of the Academy of Marketing Science*, *24*, 338–349.

Benedek, M., & Kaernbach, C. (2010). A continuous measure of phasic electrodermal activity. *Journal of Neuroscience Methods*, *190*(1), 80–91.

Berger, L., Tavares, M., & Berger, B. (2013). A Canadian experience of integrating complementary therapy in a hospital palliative care unit. *Journal of Palliative Medicine*, *16*(10), 1294–1298.

Berntson, G. G., Bigger, J. T., Eckberg, D. L., Grossman, P., Kaufmann, P. G., & Malik, M. (1997). Heart rate variability: Origins, methods, and interpretive caveats. *Psychophysiology*, *34*(6), 623–648.

Beukeboom, C. J., Langeveld, D., & Tanja-Dijkstra, K. (2012). Stress-reducing effects of real and artificial nature in a hospital waiting room. *The Journal of Alternative and Complementary Medicine*, *18*(4), 329–333.

Billman, G. E. (2013). The LF/HF ratio does not accurately measure cardiac sympatho-vagal balance. *Frontiers in Psychology*, *4*, 26.

Birnbach, D. J., King, D., Vlaev, I., Rosen, L. F., & Harvey, P. D. (2013). Impact of environmental olfactory cues on hand hygiene behaviour in a simulated hospital environment: A randomized study. *Journal of Hospital Infection*, *85*(1), 79–81.

Blechert, J., Lajtman, M., Michael, T., Margraf, J., & Wilhelm, F. H. (2006). Identifying anxiety states using broad sampling and advanced processing of peripheral physiological information. *Biomedical Sciences Instrumentation*, *42*, 136–141.

Busse, M., Stromgren, K., Thorngate, L., & Thomas, K. A. (2013). Parents' responses to stress in the neonatal intensive care unit. *Critical Care Nurse*, *33*(4), 52–59.

Campbell, J., & Ehlert, U. (2012). Acute psychosocial stress: Does the emotional stress response correspond with physiological responses? *Psychoneuroendocrinology*, *37*(8), 1111–1134.

Cannard, G. (1996). The effect of aromatherapy in promoting relaxation and stress reduction in a general hospital. *Complementary Therapies in Nursing and Midwifery*, *2*(2), 38–40.

Choi, Y., Kim, M., & Chun, C. (2015). Measurement of occupants' stress based on electroencephalograms (EEG) in twelve combined environments. *Building and Environment*, *88*, 65–72.

Cobb, S. V., Nichols, S., Ramsey, A., & Wilson, J. R. (1999). Virtual reality-induced symptoms and effects (VRISE). *Presence: Teleoperators and Virtual Environments*, *8*(2), 169–186.

Colomer, A., Fuentes-Hurtado, F., Ornedo, V. N., Guixeres, J. G., Ausín, J. M., & Alcañiz, M. (2016). A comparison of physiological signal analysis techniques and classifiers for automatic emotional evaluation of audiovisual contents. *Frontiers in Computational Neuroscience*, *10*, 74.

de Kort, Y. A. W., Ijsselsteijn, W. A., Kooijman, J., & Schuurmans, Y. (2003). Virtual laboratories: Comparability of real and virtual environments for environmental psychology. *Presence: Teleoperators and Virtual Environments*, *12*(4), 360–373.

Dedovic, K., Renwick, R., Mahani, N. K., & Engert, V. (2005). The Montreal imaging stress task: Using functional imaging to investigate the effects of perceiving and processing psychosocial stress in the human brain. *Journal of Psychiatry & Neuroscience*, *30*(5), 319–325.

Delorme, A., & Makeig, S. (2004). EEGLAB: An open source toolbox for analysis of single-trial EEG dynamics including independent component analysis. *Journal of Neuroscience Methods*, *134*(1), 9–21.

Delorme, A., Makeig, S., & Sejnowski, T. J. (2001). *Automatic artifact rejection for EEG data using high-order statistics and independent component analysis*. Proceedings of the 3rd International Workshop on ICA (pp. 457–462), San Diego, USA.

Devereux, J., Rydstedt, L., Kelly, V., Westo, P., & Buckle, P. (2004). *The role of work stress and psychological factors in the development of musculoskeletal disorders*. Guildford: University of Surrey.

Diego, M. A., Jones, N. A., Field, T., Hernandez-Reif, M., Schanberg, S., Kuhn, C., … Galamaga, R. (1998). Aromatherapy positively affects mood, EEG patterns of alertness and math computations. *International Journal of Neuroscience*, *96*(3–4), 217–224.

Diette, G. B., Lechtzin, N., Haponik, E., Devrotes, A., & Rubin, H. R. (2003). Distraction therapy with nature sights and sounds reduces pain during flexible bronchoscopy: A complementary approach to routine analgesia. *Chest*, *123*(3), 941–948.

Felnhofer, A., Kothgassner, O. D., Schmidt, M., Heinzle, A. K., Beutl, L., Hlavacs, H., & Kryspin-Exner, I. (2015). Is virtual reality emotionally arousing? Investigating five emotion inducing virtual park scenarios. *International Journal of Human-Computer Studies*, *82*, 48–56.

Fenko, A., & Loock, C. (2014). The influence of ambient scent and music on patients' anxiety in a waiting room of a plastic surgeon. *HERD: Health Environments Research & Design Journal*, *7*(3), 38–59.

García-Martínez, B., Martínez-Rodrigo, A., Zangróniz, R., Pastor, J. M., & Alcaraz, R. (2017). Symbolic analysis of brain dynamics detects negative stress. *Entropy*, *19*(196), 1–16.

Gates, J. (2008). An inquiry: Aesthetics of art in hospitals. *Australian Family Physician*, *37*(9), 761–763.

Gorski, J. A., Slifer, K. J., Kelly-Suttka, J., & Lowery, K. (2010). Behavioral interventions for pediatric patients' acute pain and anxiety: Improving health regimen compliance and outcome. *Children's Health Care*, *33*(1), 1–20.

Gray-Toft, P., & Anderson, J. G. (1981). Stress among hospital nursing staff: Its causes and effects. *Part A: Medical Psychology & Medical Sociology*, *15*(5), 639–647.

Gudmundsson, S., Runarsson, T. P., Sigurdsson, S., Eiriksdottir, G., & Johnsen, K. (2007). Reliability of quantitative EEG features. *Clinical Neurophysiology*, *118*(10), 2162–2171.

Harris, P. B., McBride, G., Ross, C., & Curtis, L. (2002). A place to heal: Environmental sources of satisfaction among hospital patients. *Journal of Applied Social Psychology*, *32*(6), 1276–1299.

Herz, R. S. (2009). Aromatherapy facts and fictions: A scientific analysis of olfactory effects on mood, physiology and behavior. *International Journal of Neuroscience*, *119*(2), 263–290.

Higuera-Trujillo, J. L., López-Tarruella, J., & Llinares Millán, C. (2017). Psychological and physiological human responses to simulated and real environments: A comparison between photographs, 360° panoramas, and virtual reality. *Applied Ergonomics*, *65*, 398–409.

Higuera-Trujillo, J. L., Montañana i Aviñó, A., & Llinares Millán, C. (2017). User evaluation of neonatology ward design: An application of focus group and semantic differential. *HERD: Health Environments Research & Design Journal*, *10*(2), 23–48.

Holm, L., & Fitzmaurice, L. (2008). Emergency Department waiting room stress: Can music or aromatherapy improve anxiety scores? *Pediatric Emergency Care*, *24*(12), 836–838.

Hyvärinen, A., & Oja, E. (2000). Independent component analysis: Algorithms and applications. *Neural Networks*, *13*(4), 411–430.

Jessee, P. O., Wilson, H., & Morgan, D. (2000). Medical play for young children. *Childhood Education*, *76*(4), 215–218.

Kawakami, K., Takai-Kawakami, K., Okazaki, Y., Kurihara, H., Shimizu, Y., & Yanaihara, T. (1997). The effect of odors on human newborn infants under stress. *Infant Behavior and Development*, *20*(4), 531–535.

Kianpour, M., Mansouri, A., Mehrabi, T., & Asghari, G. (2016). Effect of lavender scent inhalation on prevention of stress, anxiety and depression in the postpartum period. *Iranian Journal of Nursing and Midwifery Research*, *21*(2), 197–201.

Kim, S., Kim, H. J., Yeo, J. S., Hong, S. J., Lee, J. M., & Jeon, Y. (2011). The effect of lavender oil on stress, bispectral index values, and needle insertion pain in volunteers. *The Journal of Alternative and Complementary Medicine*, *17*(9), 823–826.

Kish, L. (1995). *Survey sampling*. New York, NY: John Wiley & Sons.

Kjellgren, A., & Buhrkall, H. (2010). A comparison of the restorative effect of a natural environment with that of a simulated natural environment. *Journal of Environmental Psychology*, *30*(4), 464–472.

Lang, A., Zhou, S., Schwartz, N., Bolls, P. D., & Potter, R. F. (2000). The effects of edits on arousal, attention, and memory for television messages: When an edit is an edit can an edit be too much? *Journal of Broadcasting & Electronic Media*, *44*(1), 94–109.

Lazarus, R. S., & Folkman, S. (1984). *Stress, appraisal, and coping*. New York, NY: Springer.

Leather, P., Beale, D., Santos, A., Watts, J., & Lee, L. (2003). Outcomes of environmental appraisal of different hospital waiting areas. *Environment and Behavior*, *35*(6), 842–869.

Lee, K. C., Chao, Y. H., Yiin, J. J., Chiang, P. Y., & Chao, Y. F. (2011). Effectiveness of different music-playing devices for reducing preoperative anxiety: A clinical control study. *International Journal of Nursing Studies*, *48*(10), 1180–1187.

Lehrner, J., Eckersberger, C., Walla, P., Pötsch, G., & Deecke, L. (2000). Ambient odor of orange in a dental office reduces anxiety and improves mood in female patients. *Physiology & Behavior*, *71*(1–2), 83–86.

Magaret, N. D., Clark, T. A., Warden, C. R., Magnusson, A. R., & Hedges, J. R. (2002). Patient satisfaction in the emergency department—a survey of pediatric patients and their parents. *Academic Emergency Medicine*, *9*(12), 1379–1388.

Malliani, A. (1999). The pattern of sympathovagal balance explored in the frequency domain. *Physiology*, *14*(3), 111–117.

Maxfield, L., & Melnyk, W. T. (2000). Single session treatment of test anxiety with eye movement desensitization and reprocessing (EMDR). *International Journal of Stress Management*, *7*(2), 87–101.
Moola, S., Pearson, A., & Hagger, C. (2011). Effectiveness of music interventions on dental anxiety in paediatric and adult patients: A systematic review. *JBI Database of Systematic Reviews and Implementation Reports*, *9*(18), 588–630.
Moya-Albiol, L., & Salvador, A. (2001). Empleo de estresores psicológicos de laboratorio en el estudio de la respuesta psicofisiológica al estrés. *Anales de Psicología*, *17*(1), 69–81.
Nanda, U., Chanaud, C., Nelson, M., Zhu, X., Bajema, R., & Jansen, B. H. (2012). Impact of visual art on patient behavior in the emergency department waiting room. *Journal of Emergency Medicine*, *43*(1), 172–181.
Nanda, U., Eisen, S., Zadeh, R. S., & Owen, D. (2011). Effect of visual art on patient anxiety and agitation in a mental health facility and implications for the business case. *Journal of Psychiatric and Mental Health Nursing*, *18*(5), 386–393.
Nanda, U., Pati, D., & McCurry, K. (2009). Neuroesthetics and healthcare design. *HERD: Health Environments Research & Design Journal*, *2*(2), 116–133.
Özer, N., Özlü, Z. K., Arslan, S., & Günes, N. (2013). Effect of music on postoperative pain and physiologic parameters of patients after open heart surgery. *Pain Management Nursing*, *14*(1), 20–28.
Pan, J., & Tompkins, W. J. (1985). A real-time QRS detection algorithm. *IEEE Transactions on Biomedical Engineering*, *32*(3), 230–236.
Pedrotti, M., Mirzaei, M. A., Tedesco, A., Chardonnet, J. R., Mérienne, F., Benedetto, S., & Baccino, T. (2014). Automatic stress classification with pupil diameter analysis. *International Journal of Human-Computer Interaction*, *30*(3), 220–236.
Rashidi-Fakari, F., Tabatabaeichehr, M., & Mortazavi, H. (2015). The effect of aromatherapy by essential oil of orange on anxiety during labor: A randomized clinical trial. *Iranian Journal of Nursing and Midwifery Research*, *20*(6), 661–664.
Reinerman-Jones, L., Sollins, B., Gallagher, S., & Janz, B. (2013). Neurophenomenology: An integrated approach to exploring awe and wonder. *South African Journal of Philosophy*, *32*(4), 295–309.
Routhieaux, R., & Tansik, D. A. (1997). The benefits of music in hospital waiting rooms. *The Health Care Supervisor*, *16*(2), 31–40.
Saadatmand, V., Rejeh, N., Heravi-Karimooi, M., Tadrisi, S. D., Zayeri, F., Vaismoradi, M., & Jasper, M. (2013). Effect of nature-based sounds' intervention on agitation, anxiety, and stress in patients under mechanical ventilator support: A randomised controlled trial. *International Journal of Nursing Studies*, *50*(7), 895–904.
Schwarz, N., & Strack, F. (1999). Reports of subjective well-being: Judgmental processes and their methodological implications. *Well-Being: The Foundations of Hedonic Psychology*, *7*, 61–84.
Schweitzer, M., Gilpin, L., & Frampton, S. (2004). Healing spaces: Elements of environmental design that make an impact on health. *Journal of Alternative & Complementary Medicine*, *10*(Suppl. 1), S-71–S-83.
Scott, L. D., Hwang, W. T., & Rogers, A. E. (2006). The impact of multiple care giving roles on fatigue, stress, and work rerformance among hospital staff nurses. *Journal of Nursing Administration*, *36*(2), 86–95.
Slater, M., & Steed, A. (2000). A virtual presence counter. *Presence: Teleoperators and Virtual Environments*, *9*(5), 413–434.
Slater, M., Usoh, M., & Steed, A. (1994). Depth of presence in virtual environments. *Presence: Teleoperators and Virtual Environments*, *3*(2), 130–144.
Sollers, J. J., Buchanan, T. W., Mowrer, S. M., Hill, L. K., & Thayer, J. F. (2007). Comparison of the ratio of the standard deviation of the RR interval and the root mean squared successive differences (SD/rMSSD) to the low frequency-to-high frequency (LF/HF) ratio in a patient population and normal healthy controls. *Biomedical Sciences Instrumentation*, *43*, 158–163.
Spielberger, C. D., Gorsuch, R. L., & Lushene, R. E. (1970). *Manual for the state-trait anxiety inventory*. Palo Alto, CA: Consulting Psychologists Press.
Steuer, J. (1992). Defining virtual reality: Dimensions determining telepresence. *Journal of Communication*, *42*(4), 73–93.
Sung, S. N., & Eun, Y. (2007). The effect of aromatherapy on stress of nurses working in operating room. *Journal of Korean Academy of Adult Nursing*, *19*(1), 1–11.
Suter, E., & Baylin, D. (2007). Choosing art as a complement to healing. *Applied Nursing Research*, *20*(1), 32–38.
Tennant, C., & Andrews, G. (1976). A scale to measure the stress of life events. *Australian and New Zealand Journal of Psychiatry*, *10*(1), 27–32.
Thoma, M. V., la Marca, R., Brönnimann, R., Finkel, L., Ehlert, U., & Nater, U. M. (2013). The effect of music on the human stress response. *PLOS ONE*, *8*(8), e70156.
Ulrich, R. S. (1991). Effects of interior design on wellness: Theory and recent scientific research. *Journal of Health Care Interior Design*, *3*(1), 97–109.
Ulrich, R. S., Quan, X., Zimring, C., Joseph, A., & Choudhary, R. (2004). *The role of the physical environment in the hospital of the 21st century: A once-in-a-lifetime opportunity. The center for health design for the designing the 21st century hospital project*. Concord: Robert Wood Johnson Foundation.
Valenza, G., & Scilingo, E. P. (2014). *Autonomic nervous system dynamics for mood and emotional-state recognition. Significant advances in data acquisition, signal processing and classification*. New York, NY: Springer.
Venables, P. H., & Christie, M. J. (1980). Electrodermal activity. In I. Martin & P. H. Venables (Eds.), *Techniques in Psychophysiology* (pp. 3–67). New York, NY: Wiley & Sons.
Waldon, E. G., & Thom, J. C. (2015). Recorded music in the mental health waiting room: A music medicine investigation. *The Arts in Psychotherapy*, *46*, 17–23.
Whelan, T. A., & Kirkby, R. J. (2000). Parent adjustment to a child's hospitalisation. *Journal of Family Studies*, *6*(1), 46–64.
Zhang, Y., Tzortzopoulos, P., & Kagioglou, M. (2019). Healing built-environment effects on health outcomes: Environment–occupant–health framework. *Building Research & Information*, *47*(6), 747–766.

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# Building environment information and human perceptual feedback collected through a combined virtual reality (VR) and electroencephalogram (EEG) method

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ABSTRACT

In order to accurately and quantitatively describe the influence of a building's spatial environment on subjective human perception, this research establishes a relationship framework between the spatial environment and subjective feelings, with the goal of improving occupant satisfaction and work efficiency. In pursuit of this goal, this study presents actual scenes through virtual space and introduces a new research concept for analyzing human brain data. The researchers adopted virtual reality technology in a controlled laboratory environment to compose building simulation spaces and created immersive space perceptions in response to different scenarios. Neural signal electroencephalogram (EEG) data were obtained in the simulation space from participants wearing EEG signal acquisition caps. The experiment process was divided into two phases: scene cognition and task performance. Changes in human perception, as measured on physiological, psychological, and work efficiency indexes, were examined in three environments: open natural, semi-open library, and closed basement spaces. Based on a 32-point analysis of the EEGs of 30 subjects, researchers determined four points and one region with the most significant EEG changes after scene switching. Also, by examining the EEG rhythms in the scene cognition experiment phase, the authors identified a coupling relationship between β rhythms and total time to task completion, proving the mechanistic relationship between β rhythms and work efficiency. Finally, this research revealed a correlation between subjective perception and physiological signals by analyzing the relevance of the connection between subjective questionnaire responses and the β rhythms demonstrated in the EEG experiment, and then deducing the mechanism affecting work efficiency as influenced by different environments. The results obtained show that in the context of changes to elements of a building's spatial environment, human work efficiency is most related to the β rhythms at several test points and the right temporal lobe region of the brain. Moreover, β rhythms are closely related to satisfaction with human spatial perception. Therefore, this research provides a more accurate set of reference information for building space design based on occupant satisfaction and physical and mental health. The methods and conclusions demonstrated here can be adopted as feedback for ways of obtaining more realistic information from human brain signals and using those data to optimize architectural space design.


## 1. Introduction

### 1.1. Research background

Architects have always explored the relationship between the built environment and occupants; however, different from a quantitative description of the physical environment, a subjective evaluation of the built environment based on occupants' psychological characteristics generally involves qualitative factors. [1–2]. When the interior environment changes, it can be challenging for people to accurately describe their subjective emotions, such as feelings of pressure, personal preferences, etc. As over 90% of the day may be spent inside buildings [3], the relationship between buildings and the humans who occupy them, especially the positive impact of the indoor environment on health, is not only a requirement of sustainable development and human health, but also a precondition for the sustainable development of artificial environments [4–5].

Song and others (2015) established a multi-criteria approach to developing building space optimization strategies, based on

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occupant satisfaction votes on the building space and built environment, comfort testing of the physical spatial environment, and building spatial information [5–6]. However, one research challenge is that in an actual environment, subjective evaluation of the human experience is affected by many factors such as human psychology and physiology, as well as the time of day and any contemporaneous events. Data obtained from a subjective questionnaire can be vague and lack accuracy because such questionnaires cannot exclude interference factors to the extent that human subjective perception can be reflected truly and objectively [7]. In order to solve this problem, the present research has created a new method that allows a subject to wear an instrument in a laboratory environment that measures human physiological factors and objectively and quantitatively establishes actual human perception [8–10].

In the current research analyzing the feedback of human perception related to the spatial environment, some scholars have begun to assess the relationship between human perception and building environments via EEG data. This work is based on the various effects of the physical environment on brain waves, such as when changes occur in thermal, sound, light, and air quality. For example, Shan (2019) and colleagues' experiments demonstrated that EEG rest theta bands have higher values at the FC6 and F8 locations when the subject is under low ventilation conditions, indicating that poor ventilation could lead to a relatively more pronounced sense of drowsiness in the rest condition and an increased preference for air movement and additional SBS [11–12]. Zhang (2014) studied the effects of indoor illumination on human work efficiency via an analysis of subjects' EEG data, establishing five different luminance laboratory spaces and eight cognitive experiments. The research determined that human work efficiency is highest in work environments maintaining 300 lx [13]. Choi (2019) and associates conducted experiments in various indoor air temperature environments arranged according to PMV. They used EEG measurements to investigate the effects of indoor air temperature on occupants' levels of attention [14]. However, this type of research is still in its initial stages and a comprehensive evaluation of the impact of the built environment on human beings is still lacking.

Coburn (2019) and colleagues studied the effects of natural indoor factors on human psychology, obtaining the EEG data of a number of subjects. Their work was based on laboratory experiments in which subjects wore EEG apparatuses and viewed comparative photos. The researchers found that the colors and shapes of natural indoor factors were the main features affecting human psychology [15]. Ojha (2019) and colleagues considered the effects of the urban environment on human physiological factors, using a laboratory environment to analyze changes in subjects' skin-based electrical signals. Participants' physiological responses were found primarily to be affected by changes in environmental conditions and fields of view [16].

With regards to research methods, significant body of experiments have endeavored to provide alternative high-reliability processes. For example, in terms of psychology, most research methods adopt psychological questionnaires based on a PMV model (a method of calculating the average votes) [17–18]. The subjects are asked to fill in relevant psychological questionnaires to obtain data for the experiment. These data are then used to assess psychological changes in the subjects. This method is easy to operate and has certain effects on human psychology, but it is susceptible to subjective interference and external factors [19–20]. Subjects have also been asked to wear devices for measuring human physiological factors, including electrical skin signals, heart rate, sweat rate, fingertip temperature, etc., in order to obtain signal data through experiments [21–22]. This method reflects human physiological changes, but the feedback is not mature and lacks pertinence because it is limited to the device itself. In studies of work efficiency, some researchers have asked subjects to conduct different types of cognition experiments such as character interference tests, meaningless graphics recognition, etc., in order to obtain data such as reaction time and reflection efficiency [23–24]. This method can effectively evaluate human work efficiency, but it has certain limitations. It focuses on the work efficiency of the human brain and does not establish an effective relationship between the spatial environment and human brain feedback, so it cannot be completely equivalent to work efficiency in actual work situations.

Virtual reality (VR) technology can be used to quickly construct simulations of a large number of spaces and associated environmental elements to provide immersive visual experiences. Through VR, designers and users can easily complete space evaluations and scheme optimizations, greatly reducing the design and inspection cycle. Recently, research on VR technology and the built environment has expanded. For example, VR technology is now being used to explore evidence-based design methods for applying age-appropriate color environments. By simulating actual building spaces and visual elements in a given space, construction and immersive color presentation can be explored to achieve effective evidence-based design, proving the reliability of VR technology in scientific experiments [25]. Some scholars have also used VR modeling and eye trackers to study visual cognition and behavior mechanisms in traditional villages, campuses, and transportation hubs [26]. However, using VR technology for scientific research is still in the initial stages of exploration. Although VR has many advantages in terms of virtual modeling, there are still some potential discrepancies between VR scenes and actual environments. There are two kinds of VR models, panoramic photo (or panoramic video) and virtual modeling simulations. The former requires sufficient graphical pixels, the absence of which may result in image distortion due to a single viewpoint. Also, the path and perspective cannot be adjusted according to the user's desire. While, due to the requirements of computer rendering, virtual modeling may feature defects in terms of scene details, light sense, color and texture of materials, etc., which may affect the quality of the simulation [27].

This research adopts the perspective of humanism to focus on the continuous improvement of the built environment. The study explores an innovative means of comprehensively qualitatively evaluating architectural space and design optimization. This work explores the mechanism of interaction between environmental information encoded in building space and perceptual feedback provided by the human body, revealing the laws of interaction between the two. In order to further improve the healthy environment provided by buildings, this work strives to improve upon the effective use of space resources through the cultivation of new ideas and methods.

### *1.2. Objective of this study*

In order to solve problems related to the ambiguity of human subjective evaluations and indirectness of physiological research methods, this research has constructed a comprehensive experiment framework for analyzing correlations among buildings, the environment, and human beings. There were three main objectives of this study:

1) Set up an experiment framework by adopting virtual simulation space and EEG signal acquisition, thus providing a new method for studying the relationships among buildings, the environment, and humans.

2) Establish the interaction mechanism between the spatial environment and human perception. Through an artificial environment experiments, reveal the relationships among physical, psychological, and work efficiency levels.

3) Provide a more accurate set of reference information for the design of building environments through human brain signal feedback and a more accurate means of optimizing such designs.

## 2. Methodology

This study adopted the experimental methods of VR technology, electroencephalogram (EEG) signal acquisition, and laboratory environment control technology (LEC). The experiment created an immersive spatial experience within different scenarios through the use of virtual space based on VR and LEC (as shown in Table 1). The researchers obtained EEG signal data from subjects in the simulation space through an EEG signal acquisition cap and used those data to explore correlations among the spatial environment and human physiology, psychology, and work efficiency (as shown in Fig. 1).

First, after a comparative analysis of a significant number of image samples, this study selected three substantially different types of scenes: an open natural environment, semi-open library environment, and closed basement space (as shown in Table 2). Differentiated scenario choices enhance the impact on human physiology, psychology, and work efficiency, and offer better feedback regarding changes in EEG signal data [28]. The subjects were asked to complete questionnaires and cognitive experiments in the three virtual simulation spaces. Relevant data were collected during the experiment, including EEG signals, physical environment data for the laboratory, questionnaire responses, completion times for the cognitive experiments, etc. Finally, researchers conducted cross- and multi-level comparative analyses of the experiment data.

In order to ensure the scientific validity of the experiment process and accuracy of the data, the researchers reduced the differences in EEG data from the subjects and external interference characteristics. This study required subjects to be actively thinking, have a clear sense of external stimuli, and demonstrate an expressive ability. Therefore, 30 university students (15 males and 15 females) aged 18 to 25 who were identified as physically and mentally healthy and had no recent major illnesses were selected as participants. Before the start of the experiment, basic personal information was collected from each subject, informed consent was read and signed, subjects were assisted with donning the experiment equipment, and samples of the test contents were distributed to ensure the authenticity of the data and smooth processing of the test (as shown in Figs. 2 and 3). The experiment was carried out in the following three steps.

1) After putting on the VR and EEG equipment, the subjects were asked to rest with their eyes closed for 30 s and adapt to the scene for 4 min. This closed-eye rest reduced the number of physical and psychological fluctuations in personal adaptability to the VR and EEG devices. Scene adaptation allowed subjects to immerse themselves in the virtual simulation space and provide more realistic feedback regarding their sense of the spatial experience.
2) The subjects completed a subjective spatial questionnaire survey based on the semantic differential analysis (SD) method [29]. The subjective spatial questionnaire evaluated their psychological feelings of the three different virtual simulation spaces on three levels: cognitive feelings about the scene, spatial parameters, and physical environment.
3) Researchers then conducted four cognitive experiments, according to the level of human cognition: Stroop effect, digital calculation, meaningless figure recognition, and digital symbol simulation. These were used to comprehensively evaluate the work efficiency of subjects in the different spatial scenes according to the above-mentioned three levels.

**Table 1**
Control Ranges of the Three Scenarios and Physical Laboratory Environment.

| Laboratory control parameter | Highest value | Lowest value | Average value |
|---|---|---|---|
| Temperature | 22.8 | 19.3 | 20.9 |
| PM2.5 | 75 | 7.1 | 43 |
| PM10 | 74.3 | 10 | 60.9 |
| TVOC | 0.11 | 0.03 | 0.064 |

In order to balance the adaptability and fatigue level of each subject in the experiment, the test duration was kept at about 50 min and included three scenes. Each scene was 14 to 18 min, on average. The time spent on closed-eye rest and scene adaptation in the first phase was 4.5 min for each subject. The second phase consisted of three parts: filling out a subjective questionnaire, having the cognitive experience, and completing the post-experience evaluation; these lasted about 3 min, 3 to 6 min, and 3.5 to 4.5 min, respectively. Throughout the controlled selection of subjects, experiment sequence, and experiment process, the subjects were able to become fully immersed in the scene and avoid fatigue iteration from completing lengthy tasks (as shown in Figs. 4 and 5).

### *2.1. Step one:Closed-eye rest and scene adaptation*

An EEG signal is essentially feedback from the electrophysiological activities of the brain's nerve cells; the machine is very susceptible to almost all stimuli such as psychological and sensory input, breathing, emotions, and limb movement [30–32]. After the subjects put on the instruments and equipment, they engaged in a 30-second closed-eye rest stage; this was included because of how susceptible the EEG signal is to external interference. The purpose of this stage was to reduce the negative interference of individual differences on the EEG signal data. Age, gender, personality, life experience, and other factors meant that subjects had varying degrees of adaptability and acceptability to the experiment's equipment and content; their emotions and physical condition on the day of the experiment could also possibly have caused interference [33–34]. The 30-second closed-eye rest session allowed all subjects to enter a relatively peaceful state and thus reduced the negative interference of individual differences, ultimately improving the accuracy of the data [35].

Human perception of the environment is diverse, multifaceted, and multilevel [36]. In order to guide subjects to immerse themselves in the virtual simulation space, this study included a scene adaptation stage that provided vision, hearing, and text guidance, as well as environmental control. In terms of visual guidance, the experiment took high-resolution panoramic photos of the scene via a 360° panoramic camera and imported them into a VR helmet using Unity software. This allowed subjects to observe the scene in an immersive fashion, simply by rotating their VR helmet. Regarding hearing, different background sounds were selected for the three scenes, including birds chirping, water running, people walking, reading, and engaging in conversation, etc. The sounds were played as the subjects adapted to the scenes. This auditory stimulation enhanced the sense of scene immersion. For text guidance, a description was written for each of the three scenes. By reading the corresponding guidance, subjects obtained subconscious psychological clues that enhanced their trust in the scene. In terms of environmental control, artificial control of the physical environment included temperature, humidity, and carbon dioxide and formaldehyde concentrations in a semi-circular dome-shaped cabin with a radius of 2.4 m. This created a relatively stable and

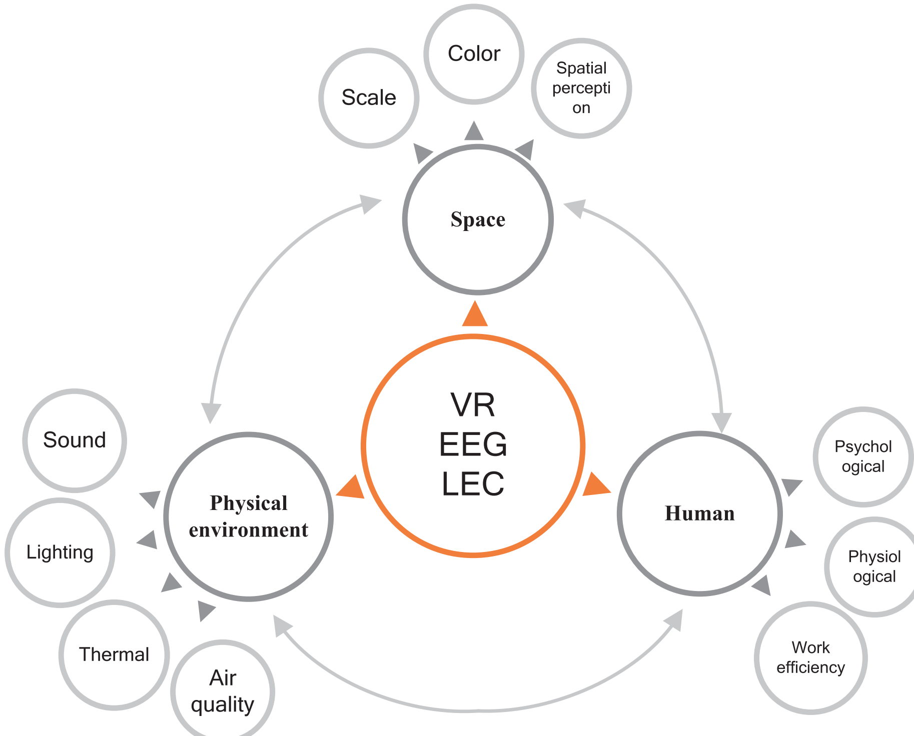



**Fig. 1.** Correlations between the building environment and human occupants.

**Table 2**
Scene Information.

| Scene name | | Filming location | Scene space information | Panoramic picture (360°) |
|---|---|---|---|---|
| S1 | Scene1 | Empty natural environment | Space form: open<br>Lighting: natural<br>Greening rate: 80%<br>Number of people: 1<br>Scene area: > 10,000㎡ Noise: quiet (birds, leaves) |  |
| S2 | Scene2 | Library in use | Space form: semi-openLighting: natural + artificial<br>Greening rate: 0%<br>Number of people: 60<br>Scene area: 2,500㎡<br>Noise: quiet (walking, talking) |  |
| S3 | Scene3 | Underground study room in use | Space form: closed<br>Lighting: artificial<br>Greening rate: 0%<br>Number of people: 15<br>Scene area: 30㎡<br>Noise: quiet (walking, talking) |  |

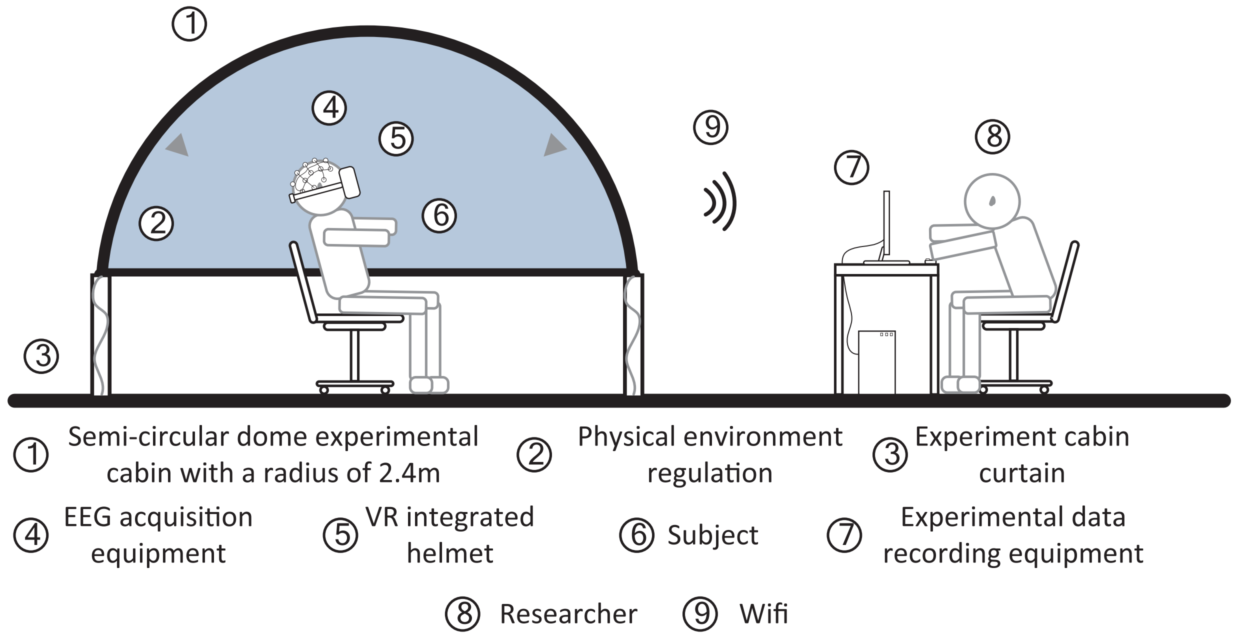



**Fig. 2.** Lab environment.

**Fig. 3.** Lab photos of the experiment.

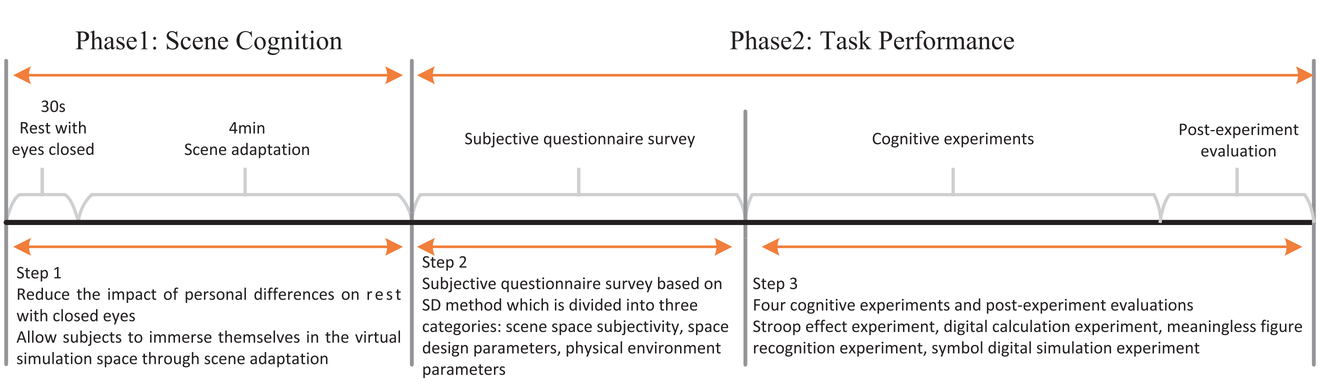



**Fig. 4.** Experiment process for each scenario.

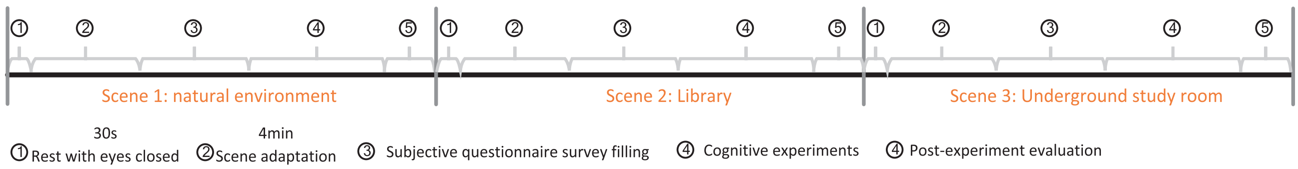



**Fig. 5.** Overall experiment process for the three scenarios.

comfortable environment and reduced interference. Through the comprehensive interaction of the above methods, the subjects were able to fully adapt to the scene and their sense of immersion was enhanced.

### 2.2. Step two:Subjective questionnaire

This study conducted a scene space psychological perception survey of subjects through a face-to-face questionnaire (as shown in Fig. 4 and Table 3). The purpose of the questionnaire was to determine the psychological changes of subjects in different scenarios so as to evaluate the degree of influence of those scenarios on participants' EEG signals.

The content of the subjective questionnaire was divided into three categories: subjective feelings of the scene space, spatial design parameters, and feelings regarding the physical environment. It comprehensively evaluated human perception of the virtual simulation on three levels: environment, space, and psychology. Since subjective feelings of the scene space mainly reflected an evaluation of the particular subject's psychology, it was divided into two groups: before and after the experiment. Each consisted of four sub-questions: VR environment adaptability, VR environment satisfaction, emotion, and concentration. Feelings regarding the spatial design parameter mainly reflected an evaluation of the subject's feelings about the environment, including four sub-questions of spatial scale cognition, spatial scale comfort, spatial color cognition, and spatial color comfort. In the end, feelings related to the physical environment parameters mainly reflected an evaluation of the environment, including five sub-questions: thermal comfort, thermal environment acceptability, perception of the light environment, adaptability of the light environment, and overall perception of the space environment.

In this study, the scoring evaluation method for the subjective questionnaire was a 7-point semantic difference scale [37–38]. The scale was divided into seven levels, with one end representing "negative" and the other indicating "positive." In order to better compare the differences between topics, the scoring scale was quantified as: −3, −2, −1, 0, 1, 2, and 3, ranging from −3 (most negative) to 3 (most positive) and 0 being neutral. "Negative" and "positive" were then converted into more direct evaluation terms according to topic types such as uncomfortable / comfortable to evaluate VR environment adaptability, narrow / spacious to assess spatial scale, etc. (as shown in Table 3).

### 2.3. Step three:Task performance phase

Human work efficiency is affected by a variety of factors [39]. In order to obtain the most reasonable and scientific evaluation data, this study set up four types of cognitive experiments based on human psychology: Stroop effect, digital calculation, meaningless figures recognition, and symbolic digital simulation. Together, these comprehensively evaluated subjects' work efficiency by recording the times taken to complete the four cognitive experiments [40–41] (as shown in Table 4). If the subject answered incor-

**Table 3**
Test Framework for Subjective Questionnaire.

| Test item | Evaluation type | Test child | Evaluation scale | Parameter unit |
|---|---|---|---|---|
| Subjective feelings (before experiment) | Cognitive (physiological) | VR environment adaptability | Not adapted-Adapted | Score [−3, −2, −1,0,1,2,3] |
| | Feeling (psychological) | VR environment satisfaction | Dissatisfied-Satisfied | |
| | Cognitive (physiological) | Concentration | No-Yes | |
| | Feeling (psychological) | Emotion | Irritable-Calm | |
| Space design parameters | Cognitive (physiological) | Spatial scale cognition | Small space-Big space | |
| | Feeling (psychological) | Spatial scale comfort | Narrow-Spacious | |
| | Cognitive (physiological) | Spatial color recognition | Cold-Warm | |
| | Feeling (psychological) | Spatial color comfort | Uncomfortable-Comfortable | |
| Physical environment parameters | Cognitive (physiological) | Thermal comfort | Cold-Hot | |
| | Feeling (psychological) | Thermal environment acceptability | Uncomfortable-Comfortable | |
| | Cognitive (physiological) | Light environment perception | Dark-Light | |
| | Feeling (psychological) | Light environment acceptability | Uncomfortable-Comfortable | |
| | Feeling (psychological) | Overall space environment perception | Uncomfortable-Comfortable | |
| Subjective feelings (after experiment) | Cognitive (physiological) | VR environment adaptability | Not adapted-Adapted | |
| | Feeling (psychological) | VR environment satisfaction | Dissatisfied-Satisfied | |
| | Cognitive (physiological) | Ability to concentrate | No-Yes | |
| | Feeling (psychological) | Emotion | Irritable-Calm | |

**Table 4**
Cognitive Experiments.

| Cognitive experiment | Psychological level | Specific Experiment settings | Experiment example | |
|---|---|---|---|---|
| | | | **Example 1** | **Example 2** |
| Stroop effect experiment | Perceptual function | A series of visual signal questions is given and subjects are asked to identify the colors of all visual signals or visual signals with incorrect colors; response time length is recorded. | Red Green Black Brown Yellow Blue Please say the color of the word. | Yellow Blue Brown Green Orange Purple Please say the word that is wrong. |
| Digital calculation experiment | Thought function | Different degrees of calculation equations are given. Subjects are required to calculate the results of the equations or judge their correctness; response time length is recorded. | 8+4X6-2=? Please calculate the following equation. | 23+(24÷3)X2=38 Please judge the correctness of the equation. |
| Meaningless figure recognition experiment | Learning and memory functions | Three similar figures are given and subjects are asked to memorize them. They are then required to find the memory figure that appears and then the same two figures in a series; reaction time length is recorded. |  Please<br>1 2 3<br>select the graphic that just appeared. |  Please<br>1 2 3 4 5<br>select the two identical graphics. |
| Symbolic digital simulation experiment | Expression function | One to four numbers are given with each corresponding to a character. Participants are asked to memorize them. They are then given a randomly arranged character or number sequence and asked to name the corresponding number or character column; response time length is recorded. | 3 2 1 4 Please say the following numbered characters. | # B Q @ Please state the following number order |

rectly, they received a signal of "wrong answer" and the question remained until the subject answered correctly. Therefore, the total time for experiment completion was the total length of time it took to achieve 100% accuracy. This eliminated interference from wrong answers. Through the difference-based statistical method of "total duration," subjects experienced the same workloads and subtle differences in value could more accurately be illustrated with regards to work efficiency. This was of great benefit in the next step of the research, where the relationship between EEG rhythm and work efficiency was explored.

The Stroop effect experiment represents human perceptual function [42]. The experiment gives a series of visual signal questions, and then asks subjects to speak aloud the color of all visual signals or visual signals with incorrect colors. It then records the response time length. The digital calculation indicates human thought function [43]. The test gives different degrees of calculation equations. Subjects are required to calculate the results of the equations or judge their correctness. Again, response time length is recorded. Meaningless figure recognition experiments represent human learning and memory function [44]. The experiment first gives three similar figures and asks the subject to memorize them. The test then requires the subject to find the memory figure that appears. Finally, the subject is asked to find the same two figures in a series. This test also records reaction time length. The symbolic digital simulation experiment represents the human expression function [45]. First, it gives one to four numbers, with each corresponding to a character. The test then asks the subject to memorize them. Next, the subject is given a randomly arranged sequence of characters or numbers and asked to identify the corresponding number or character column. Finally, the test records the response time length.

## 3. Results and discussion

### 3.1. Search for target point

The amplitude of an EEG represents the intensity of the brain potential, which is closely related to synchronous discharged numbers of neurons and their arrangement direction [46,47]. If the number of neurons involved in the synchronous discharge is substantial and the arrangement direction consistent, the distance between the neurons and recording electrode is close and the amplitude of the neurons will increase; otherwise, it will decrease. Brain waves can be divided into four categories, according to the amplitude: low amplitude < 25 μV; medium amplitude 25 ~ 75 μV; high amplitude 75 ~ 150 μV; ultra-high amplitude >150 μV [48,49].

The EEG data from 30 subjects in three different scenarios were obtained from this experiment. The total amount of data reached 900 million data points. Based on the analysis of this significant body of data, this research first extracted Ph points as the research object. Ph points indicate the most violent EEG changes in the scene adaptation stage, after scene switching. Due to the sizeable body of data involved in this research, the logic for generating the research conclusions were as follows:

1) In the scene adaptation stage, a stable 10 s period of brain waves were selected from each of the 30 participants, and interference factors such as blinking, head turning, and poor eye contact were eliminated.
2) A correlation analysis of the bands in the three scenarios (i.e., S1 & S2, S2 & S3, and S1 & S3) was conducted in pairs. By calculating the correlation coefficients, $R_A$ was marked for | R | < 0.2 (i.e., the absolute value of the correlation coefficient) and $R_B$ was marked for | R | ≥ 0.2. The $R_A$ value showed significant differences in EEG potential when two scenarios were compared, while $R_B$ showed no significant differences (as shown in Fig. 6). In Fig. 7, the redder the point is, the more significant the difference in EEG potential. The bluer the point is, the less significant the difference.
3) The total statistics mount of $R_A$ at 32 points for the 30 subjects was counted and sorted. The top four points in the ranking were marked $P_{h1\text{-}4}$, indicating the most dramatic changes in EEG (as shown in Table 5; because of space limitations, only the correlation coefficient distributions of some randomly selected points are listed).
4) $P_{h1\text{-}4}$ were determined to be F7 in the frontal lobe, CP2 in the parietal lobe, FC6 in the right temporal lobe, and P3 in the occipital lobe. They are also marked in the EEG bitmap shown in Fig. 7.
5) According to the statistics, from the distribution of the whole area, the differences in EEG potential of the right temporal lobe region were more significant than in other regions of the brain (as shown in Table 5).

After a pairwise correlation comparison of the EEG potentials, obtained before and after the three switching scenarios, $P_{h1\text{-}4}$ were determined to be F7 in the frontal lobe, CP2 in the parietal lobe, FC6 in the right temporal lobe, and P3 in the occipital lobe. From

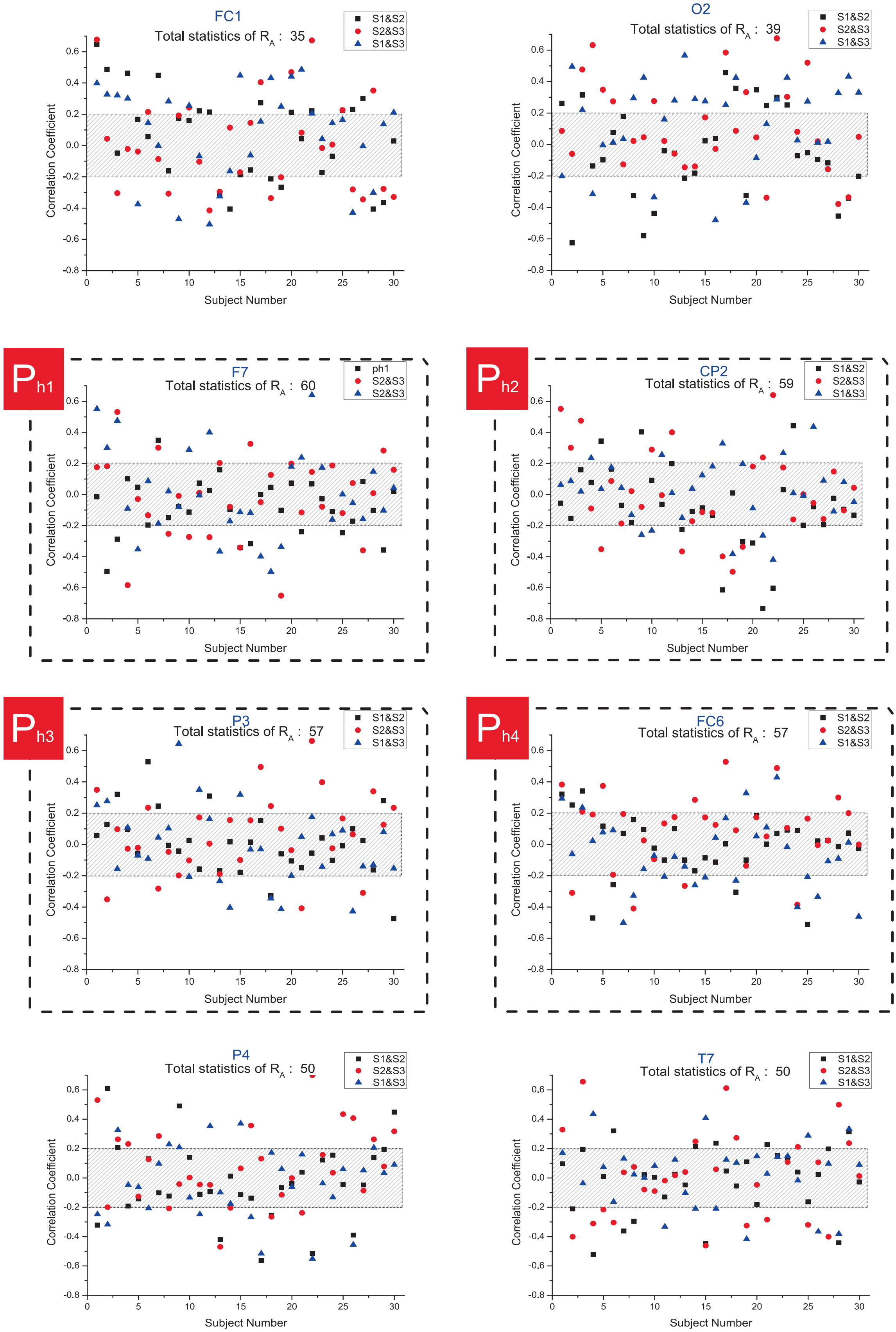



**Fig. 6.** Correlation coefficient distribution of representative points (i.e., | R | in maxium, | R | in minimum, | R | in median).

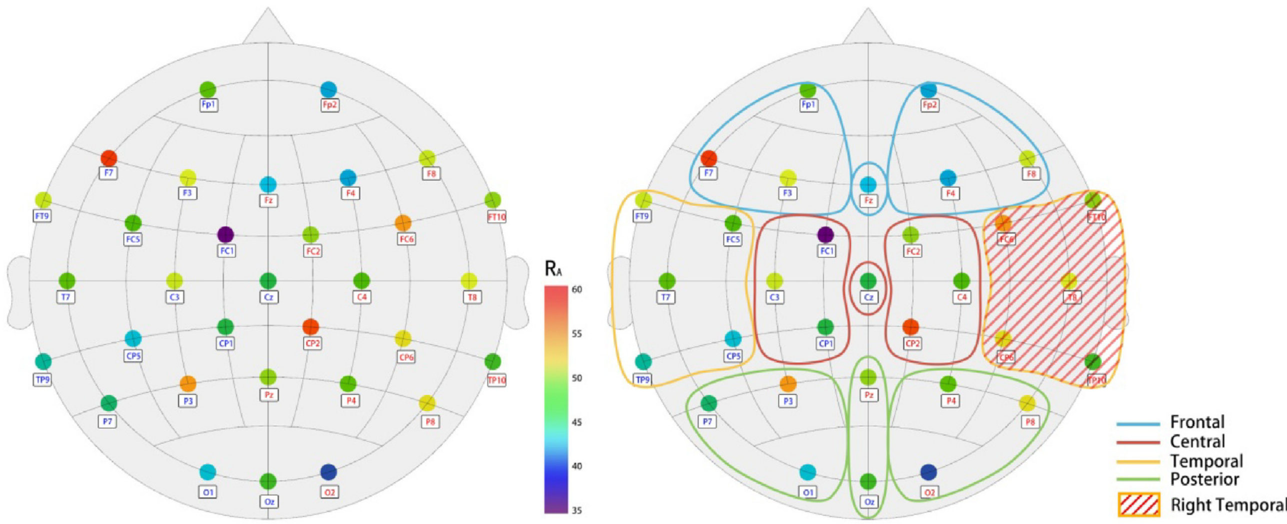



**Fig. 7.** Correlation distribution of scene switching in brain points (the redder the point, the more significant the difference in EEG potential; the bluer the point, the less significant the difference in EEG potential).

**Table 5**
$R_A$ Statistics for 32 Test Points.

| **Front** | | **Central** | | **Temporal Left** | | **Temporal Right** | | **Posterior** | |
|---|---|---|---|---|---|---|---|---|---|
| Position | Total number of $R_A$ statistics | Position | Total number of $R_A$ statistics | Position | Total number of $R_A$ statistics | Position | Total number of $R_A$ statistics | Position | Total number of $R_A$ statistics |
| F7 | 60 | Cz | 47 | FT9 | 52 | FC6 | 57 | P7 | 45 |
| Fp1 | 50 | FC1 | 35 | FC5 | 49 | FT10 | 51 | P3 | 57 |
| Fp2 | 41 | FC2 | 51 | TP9 | 44 | T8 | 53 | Pz | 51 |
| F8 | 52 | C3 | 52 | T7 | 50 | TP10 | 48 | P4 | 50 |
| F3 | 53 | C4 | 49 | CP5 | 43 | CP6 | 54 | P8 | 54 |
| Fz | 42 | CP1 | 47 | | | | | O1 | 43 |
| F4 | 41 | CP2 | 59 | | | | | Oz | 48 |
| | | | | | | | | O2 | 39 |
| **FAvg. = 48.42857** | | **CAvg. = 48.57143** | | **TLAvg. = 47.6** | | **TRAvg. = 52.6** | | **PAvg. = 48.375** | |

the overall division, the differences in EEG potential in the right temporal lobe were determined to be more significant than those in other regions. Therefore, this research focused on $P_{h1\text{-}4}$ in the right temporal lobe region in order to further study the interaction between the human brain and spatial environment.

### *3.2. Establishing a relationship between brain rhythm and work efficiency*

EEGs with consistent patterns, periodicities, and recurrences are called EEG rhythms [50]. A significant number of medical and neurological studies have shown that EEG rhythms are closely related to the working state of the human brain [51–54]. For adults, the range of 0.5–4 Hz is denoted as the delta band, which is mainly related to deep sleep. The range of 5–7 Hz is the theta band, which is considered the transition between drowsiness and consciousness. The range of 8–13 Hz is the alpha band, which is prominent in relaxed awareness but attenuates or disappears with concentration or attention. The range of 14–30 Hz is the beta band, which is related to active thinking, attention, and solving specific problems. Finally, the range of 30–45 Hz is often called the gamma band; the amplitude is usually smaller than those of the other bands [55,56] (as shown in Table 6).

As described above, it was determined that the right temporal lobe region had the most significant changes before and after the scene switch, which was consistent with the conclusion that the β wave was mainly located in the temporal and frontal regions [57]. The β wave reflects active thinking, attention, or the solving of specific problems. It has an important relationship with the correlation mechanism between scene environment and work efficiency, the focus of the present research.

**Table 6**
EEG Rhythm Distribution and Characteristics[54]

| **Rhythm** | **Frequency (HZ)** | **Amplitude (μV)** | **Location & Function** |
|---|---|---|---|
| Delta (δ) | 1–4 | Above 50 | Frontal in adults (sleep); Posterior in children (slow wave sleep) |
| Theta (θ) | 5–7 | Above 50 | Occipital region;Children, drowsy adults, emotional distress |
| Alpha (α) | 8–13 | 50–100 | Occipital region;Relaxed wakeful rhythm with eyes closed |
| Beta (β) | 14–30 | 20 | Temporal and frontal regions; mental activity / excitement |
| Gamma (γ) | • 30 | Very small | Sensory cortex;Sensory perception / binding of different neurons |

Based on the energy distributions of $Ph_{1\text{-}4}$ corresponding to different rhythms, this study further obtained the coupling relationship between β and total time length of the task performance stage. The operational method of the cognitive experiment was that when subjects answered incorrectly, they received a “wrong answer” prompt until they answered the question correctly; they were then allowed to switch to the next question. Therefore, the total time of the task completion stage was the total length of time under the premise of 100% work accuracy, eliminating the interference of wrong answers. The generation logic of the research conclusions was as follows:

1) Experiment data at the task performance stage were selected, and the EEG voltage signals of subjects converted into frequency signals. Then, the total energy values of points $P_{h1\text{-}4}$ were compared to the EEG rhythms of α, β, and θ.
2) Since the β wave is most closely associated with being conscious or in an awake, attentive, and alert state, the coupling relationship between the total duration T (including the four types of questions Q1-Q4) of the individual cognitive experiment and the β rhythms were counted. The variable T was the length of time recorded with guaranteed accuracy (as shown in Table 7).

After a statistical regression analysis was conducted by combining the total duration T of the cognitive experiment (including the four types of questions, Q1-Q4) with the energy proportion of the β rhythm, it was determined that there was an inverse relationship between the two. The larger the β rhythm energy proportion, the shorter the time spent on task completion. The smaller the β rhythm energy proportion, the longer the time spent on task completion. The β rhythm was also determined to be directly proportional to the efficiency of the human brain's work state. When the β rhythm is relatively active, it is beneficial for the human brain to complete a task efficiently (as shown in Fig. 8).

Therefore, the conclusion at this stage of the experiment was that there was a proportional relationship between the β rhythm and work efficiency of the human brain. This served as the foundation for the next stage, in which the excitation mechanism of the β rhythm in different scenarios was studied.

Fig. 8 shows the relationship between the time(s) and energy ratios of the βrhythms (%) for each of the four questions. Generally, each question presented different degrees of negative correlation. (The red line is the fit line for the data, the dotted gray line is the 99% confidence interval curve, and k is the slope of the red line). For question type 1, k = -0.284, |t| = 0.909; for question type 2, k = -0.096, |t| = 0.485; for question type 3, k = -0.13, |t| = 0.368; and for question type 4, k = -0.892, |t| = 2.331. (Since the number of samples in each group was < 30, the *t*-test was more statistically significant.) Judging from the results, question type 4 was most significantly correlated under the standard inspection level a = 0.05, while question type 3 was least significantly correlated.

3) The T and β of the 30 subjects were fit into a relationship that preliminarily established a connection between T and the β rhythm as a result of the first-order function. Thus, β was a function of T, and there was an inverse relationship between the two (as shown in Fig. 9).

$$T = f(\beta, C)$$

Fig. 9 plots the four groups of samples for the four questions, facilitating an analysis of the correlation of total duration T and total β rhythm energy proportion. (The red line is the fit line for the data, the dotted gray line is the 99% confidence interval curve, and k is the slope of the red line.) The overall data were tested by a Z-test. The results show a negative correlation (k = -0.387, p = 0.076). For $p \geq 0.05$, it is clear that the fit formula had a high probability of establishment.

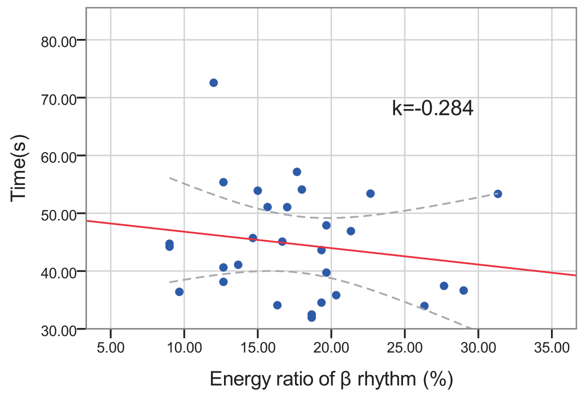
### 3.3. Study of the correlation between scene environment and β rhythm

According to the conclusions drawn above, the energy of the β rhythm affected the work efficiency of the subjects, and the relationship between the two was proportional. Therefore, this section discusses β rhythm excitation in the human brain in three different scenarios (i.e., open natural environment, semi-open space, and closed basement). The generation logic of the research conclusions was as follows:

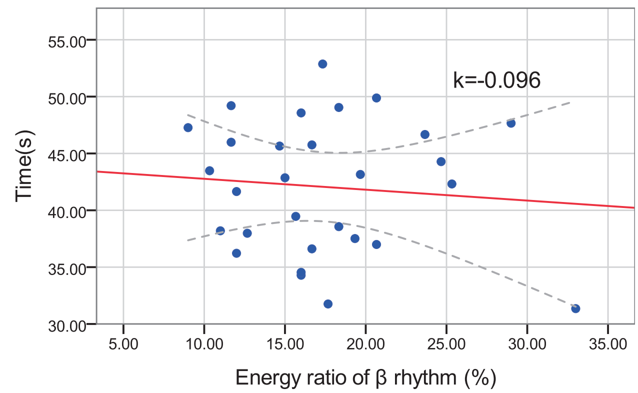
1) Determine the total energy of the β rhythm in the three scenes

**Table 7**
Statistics on the Total Duration of Cognitive Experiments T (including four types of questions Q1-Q4) and β Rhythm.

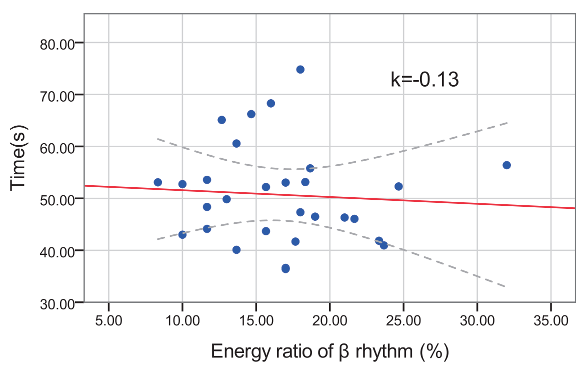
| Subject No. | Q1 | | Q2 | | Q3 | | Q4 | |
|---|---|---|---|---|---|---|---|---|
| | $\bar{E}_{\beta1}$(%) | $\bar{T}_1$(s) | $\bar{E}_{\beta2}$(%) | $\bar{T}_2$(s) | $\bar{E}_{\beta3}$(%) | $\bar{T}_3$(s) | $\bar{E}_{\beta4}$(%) | $\bar{T}_4$(s) |
| 1 | 15.00 | 53.91 | 11.67 | 45.99 | 14.67 | 66.22 | 13.33 | 58.68 |
| 2 | 17.00 | 51.06 | 18.33 | 49.05 | 18.00 | 74.81 | 18.33 | 89.82 |
| 3 | 12.67 | 55.37 | 11.00 | 38.20 | 11.67 | 53.56 | 10.67 | 50.44 |
| 4 | 12.00 | 72.57 | 12.00 | 36.22 | 11.67 | 48.35 | 10.67 | 86.61 |
| 5 | 15.67 | 51.08 | 14.67 | 45.65 | 12.67 | 65.09 | 11.00 | 78.45 |
| 6 | 9.00 | 44.22 | 9.00 | 47.27 | 8.33 | 53.09 | 7.67 | 84.39 |
| 7 | 12.67 | 40.63 | 16.67 | 45.75 | 13.00 | 49.84 | 12.33 | 68.97 |
| 8 | 9.67 | 36.40 | 10.33 | 43.48 | 10.00 | 52.74 | 10.33 | 53.78 |
| 9 | 31.33 | 53.35 | 33.00 | 31.35 | 32.00 | 56.39 | 29.33 | 51.65 |
| 10 | 19.67 | 39.74 | 20.67 | 36.99 | 18.67 | 55.78 | 20.00 | 56.72 |
| 11 | 29.00 | 36.64 | 29.00 | 47.66 | 23.33 | 41.84 | 25.00 | 52.64 |
| 12 | 19.33 | 43.63 | 20.67 | 49.88 | 18.00 | 47.33 | 23.33 | 71.24 |
| 13 | 16.33 | 34.09 | 16.00 | 34.29 | 17.00 | 36.62 | 16.00 | 85.52 |
| 14 | 17.67 | 57.16 | 18.33 | 38.56 | 15.67 | 43.69 | 17.67 | 72.99 |
| 15 | 26.33 | 33.96 | 24.67 | 44.28 | 23.67 | 40.95 | 24.67 | 54.47 |
| 16 | 9.00 | 44.73 | 11.67 | 49.20 | 10.00 | 43.01 | 10.33 | 72.79 |
| 17 | 44.67 | 38.10 | 47.67 | 45.36 | 46.67 | 47.00 | 46.00 | 66.93 |
| 18 | 20.33 | 35.83 | 19.33 | 37.51 | 19.00 | 46.48 | 19.67 | 68.45 |
| 19 | 12.67 | 38.13 | 16.67 | 36.61 | 17.00 | 53.04 | 17.67 | 57.03 |
| 20 | 27.67 | 37.43 | 25.33 | 42.32 | 24.67 | 52.29 | 26.67 | 44.67 |
| 21 | 21.33 | 46.91 | 15.67 | 39.46 | 21.00 | 46.31 | 21.00 | 67.82 |
| 22 | 18.67 | 31.95 | 15.00 | 42.86 | 16.00 | 68.29 | 14.00 | 62.58 |
| 23 | 19.33 | 34.54 | 19.67 | 43.15 | 17.67 | 41.68 | 16.67 | 62.87 |
| 24 | 19.67 | 47.90 | 17.33 | 52.87 | 18.33 | 53.14 | 18.33 | 57.36 |
| 25 | 16.67 | 45.09 | 12.00 | 41.65 | 11.67 | 44.13 | 15.67 | 60.10 |
| 26 | 22.67 | 53.40 | 23.67 | 46.67 | 21.67 | 46.06 | 23.33 | 65.43 |
| 27 | 13.67 | 41.08 | 12.67 | 37.98 | 13.67 | 40.10 | 16.67 | 63.37 |
| 28 | 14.67 | 45.72 | 16.00 | 34.54 | 15.67 | 52.18 | 17.33 | 66.14 |
| 29 | 18.00 | 54.10 | 16.00 | 48.57 | 13.67 | 60.56 | 13.67 | 53.34 |
| 30 | 18.67 | 32.49 | 17.67 | 31.76 | 17.00 | 36.40 | 19.33 | 53.39 |



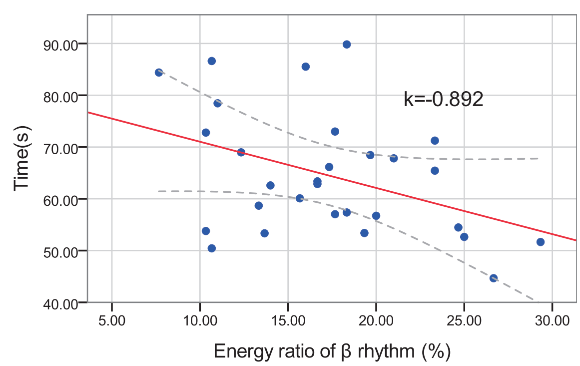

Question Type 1: Stroop effect experiment




Question Type 2: Digital calculation experiment




Question Type 3: Meaningless figure recognition experiment




Question Type 4: Symbolic digital simulation experiment

**Fig. 8.** Regression analysis of the ratio of time duration T to β rhythm energy proportion.

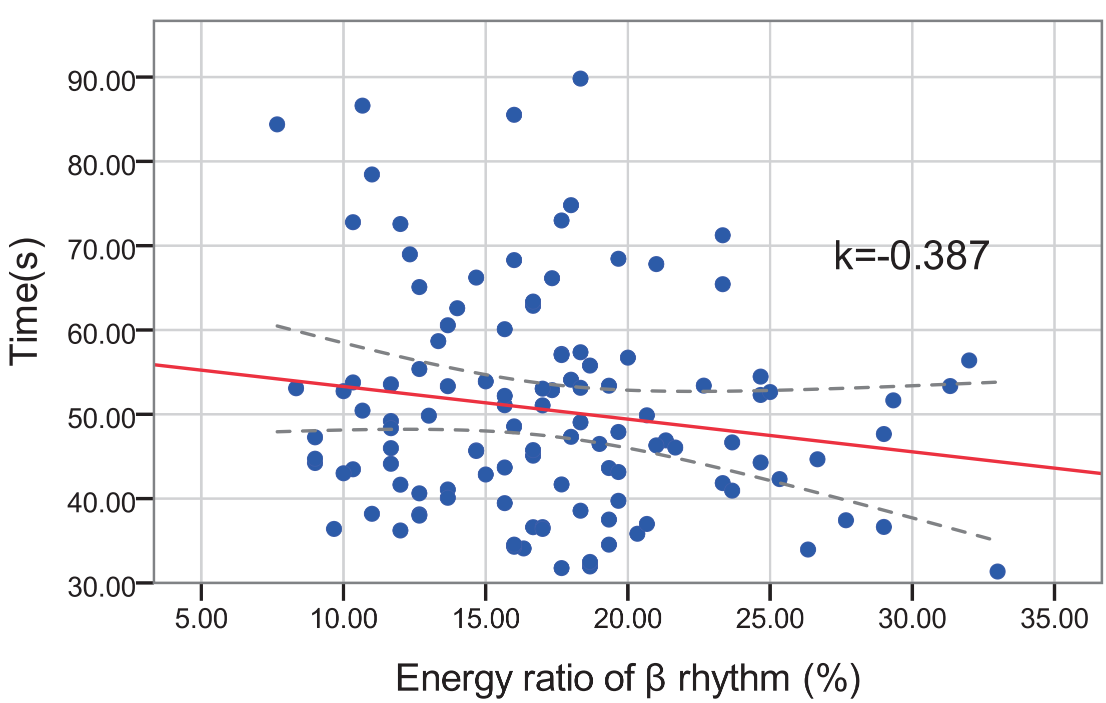



**Fig. 9.** Regression analysis of the proportion of total duration T and total β rhythm energy proportion.

In the scene adaptation stage, a stable 10 s interval of brain waves were selected from the 30 subjects, and interference factors such as blinking, head turning, and poor eye contact were eliminated. The total energy of the β rhythm in this 10 s sample was tabulated. According to the statistics, the natural environment of Scenario 1 had the highest total energy of β rhythms generated by the subjects. In the artificial environments of Scenarios 2 and 3, the total energy levels of the β rhythms were similar, and the space with larger dimensions was slightly better than the smaller of the two (as shown in Table 8). The total energy ranks of the β rhythms in the three scenes were as follows:

**Table 8**
Statistics for the Total Energy Levels of the β Rhythms in the Three Environments.

| Subject | S1 (Power dB) | S2(Power dB) | S3(Power dB) |
|---|---|---|---|
| N1 | 27.78 | 12.14 | 193.44 |
| N2 | 308.81 | 289.82 | 69.1 |
| N3 | 98.96 | 46.07 | 112.98 |
| N4 | 63.05 | 28.08 | 26.21 |
| N5 | 168.32 | 114.21 | 252.24 |
| N6 | 12.58 | 30.9 | 11.38 |
| N7 | 8.63 | 7.9 | 18.81 |
| N8 | 51.44 | 84.79 | 98.23 |
| N9 | 288.8 | 323.86 | 274.03 |
| N10 | 315.75 | 214.96 | 57.79 |
| N11 | 93 | 94.99 | 106.29 |
| N12 | 60.46 | 122.97 | 112.35 |
| N13 | 46.35 | 59.3 | 133.87 |
| N14 | 121.64 | 77.71 | 66.52 |
| N15 | 347.7 | 148.54 | 144.11 |
| N16 | 43.73 | 33.72 | 13.1 |
| N17 | 175.84 | 273.62 | 314.45 |
| N18 | 31.69 | 45.63 | 48.13 |
| N19 | 27.86 | 30.73 | 16.83 |
| N20 | 58.64 | 31.92 | 34.7 |
| N21 | 155.01 | 106.18 | 101.55 |
| N22 | 26.26 | 20 | 19.07 |
| N23 | 32.57 | 50.41 | 98.98 |
| N24 | 23.21 | 30.07 | 29.94 |
| N25 | 24.53 | 188.49 | 96.44 |
| N26 | 82.51 | 66.96 | 76.34 |
| N27 | 43.54 | 27.7 | 22.14 |
| N28 | 170.67 | 95.57 | 77.81 |
| N29 | 119.63 | 34.51 | 74.45 |
| N30 | 300.08 | 181.03 | 74.59 |
| **Mean** | **110.97** | **95.76** | **92.53** |

$$\overline{\beta}_{s1} > \overline{\beta}_{s2} > \overline{\beta}_{s3}$$

2) Analysis of differences in scene parameters

During the experiment, the researchers administered a subjective questionnaire to the subjects. The questions were designed in pairs. One indicated the participant's perception of a certain situation, as reflected on the physiological level (i.e., vision, hearing, touch, temperature, and light). The other was a human evaluation of the situation, as reflected at the psychological level. Information is transmitted to the brain through physiological responses, and mental activity or emotions are generated after the brain makes a judgment. The scale of the subjective questionnaire followed a 7-point evaluation method. One end of the scale was −3, representing the most negative evaluation (e.g., inadaptability, dissatisfaction, discomfort, etc.). The other end of the scale was 3, representing the most positive evaluation (e.g., adaptation, satisfaction, comfort, etc.). The 0 value indicated a neutral evaluation.

Next, this study conducted statistical correlation analyses of the β rhythms in the 10 s and the scores of the subjective questionnaires addressing the three environments (as shown in Fig. 10). It was determined that physiological aspects (i.e., SSRV, SCRV, TSV, and LSV) were less correlated with β rhythms, while psychological aspects (i.e., SSCV, SCCV, TCV, LCV) were more correlated with β rhythms. That is to say, the effect on the beta waves on a physiological level was smaller than the effect on the beta waves on a psychological level. For example, even if the subject perceived that the space dimension was narrow, if they also judged that the space scale was comfortable, the proportion of the corresponding β

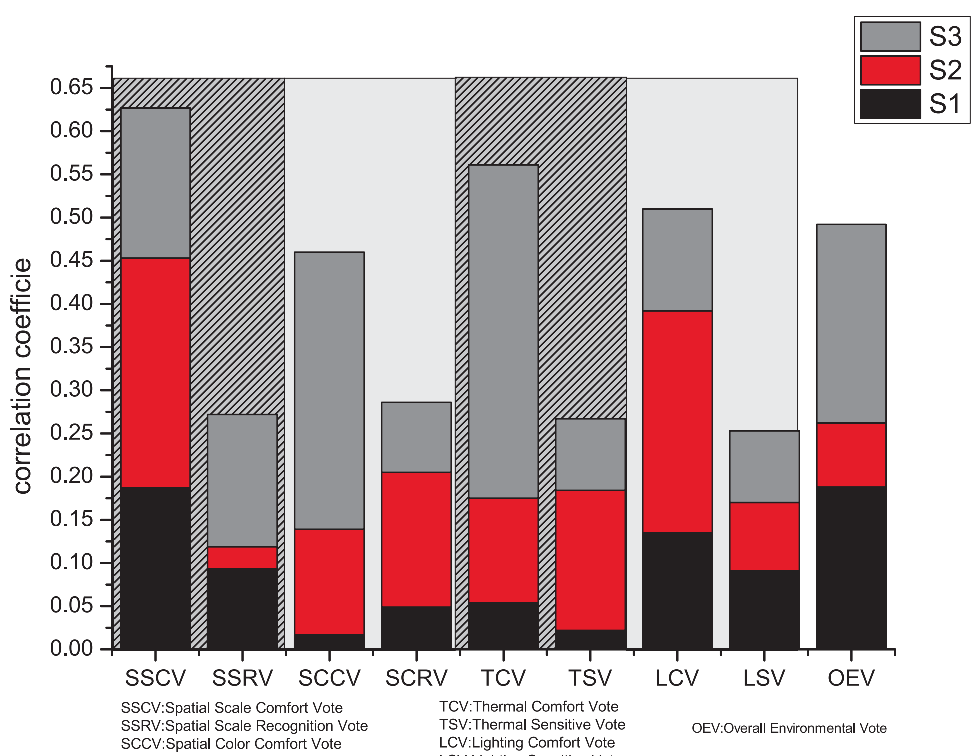



**Fig. 10.** Correlation analysis of subjective questionnaires and β rhythm energy proportions in the three sample environments.

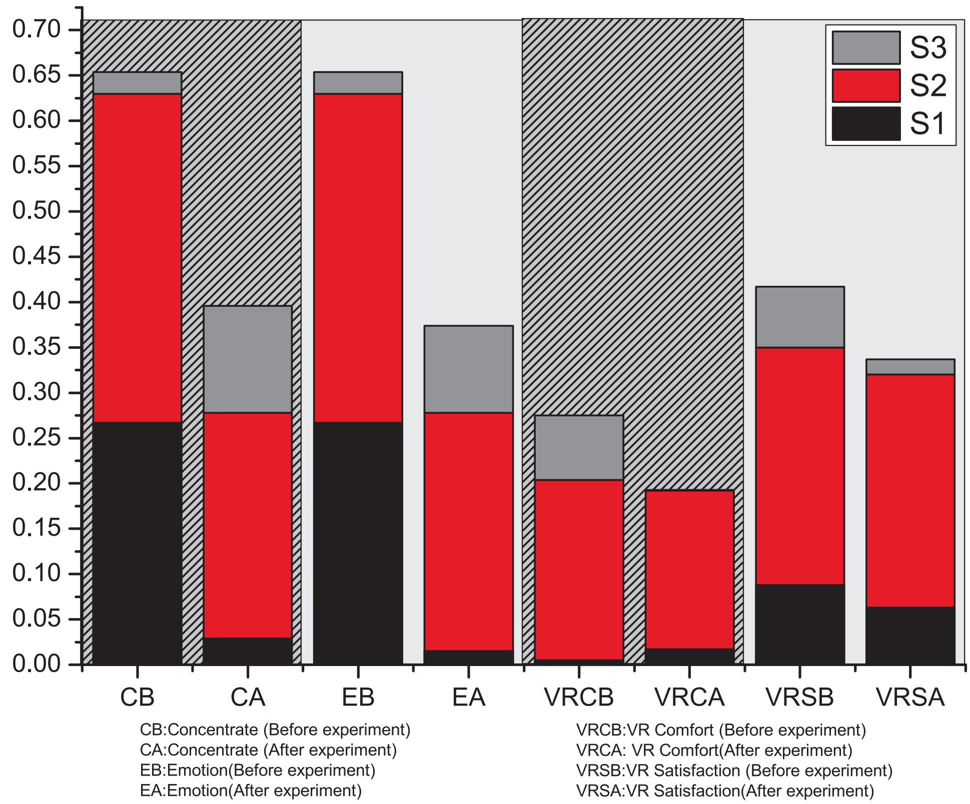



**Fig. 11.** Correlation analysis of the subjective questionnaire and β rhythm energy proportion before and after the experiment.

rhythms was larger and work efficiency in the environment higher. As another example, even if the temperature of the environment was relatively low, if the subject felt that the environment was comfortable (as determined through feedback from the brain), the proportion of the corresponding β rhythms increased, and thus the work efficiency in the space was higher.

The subjective questionnaire also included questions on human emotions, levels of attention, comfort, and satisfaction in response to the VR environment. The subjects were required to make evaluations before and after the experiment in response to each scene (as shown in Fig. 11). This study found that the correlation coefficients between the questionnaire scores before the experiment and β rhythm energy proportions were greater than in the data collected after the experiment. Among the aspects addressed, human emotion and attention were significantly correlated with the β rhythm energy proportion, indicating that β rhythm is largely affected by human psychology. Therefore, subjective satisfaction will significantly affect a subject's work efficiency. It was also determined that the comfort and satisfaction of the VR environment did not significantly correlate with the β rhythm energy proportion, indicating that the subjects felt immersed in the experiment, the reduced EEG rhythm was due to wearing the equipment, and the results were minimally affected by virtual simulations in a laboratory environment.

## 4. Conclusions and outlook

This research adopted VR and LEC to form a high simulation building experiment space and an immersion space for measuring feelings. The experiment was conducted in different VR scenes. The EEG data from the subjects in response to the simulation space were obtained by asking participants to wear an EEG equipment. Through the two phases of scene cognition and task performance experiments, changes in three indexes of human perception (i.e., physiological, psychological, and work efficiency) in three different environments (i.e., open natural environment, semi-open library environment, and closed basement space) were examined. Based on the data analysis, the conclusions are as follows:

1) A set of innovative laboratory tests method combining VR and EEG was established. In this research, VR technology was used to build an immersive simulation environment in the laboratory, which enhanced the simulation degree in vision, hearing, feeling, and other dimensions. EEG data from the human brain was acquired in response to three different environments, in order to analyze the effect mechanism of building space environment on human physiology and work efficiency. This method can be used in various spaces such as businesses, offices, underground, special environments, etc., in order to study the mechanism of space environment on occupants' physiological feedback.
2) From the correlation analysis of brain potential and before-after scene switching, the most significant four points and one area (i.e., right temporal lobe) were obtained via a step-by-step screening analysis of 900 million data points from the EEG data of 30 subjects, 32 points, and three space environments.
3) By analyzing the EEG rhythms of 30 subjects, the coupling relationship between β rhythm and total time length for guaranteed accuracy of task execution was obtained, and the functional relationship between β rhythm and work efficiency found. This proves that β rhythms promote work efficiency.
4) Through a correlation analysis of the subjective questionnaire survey and β rhythms from the EEG, the connection between subjective feelings and physiological signals was

obtained and the mechanism of emotion on work efficiency under the influence of the environment deduced. The results show that when environmental factors related to building space were changed, people's work efficiency in the particular environment was related to their β rhythms in their right temporal lobe area. Thus, β rhythms are closely related to occupant satisfaction level of spatial perception, or in other words, psychological decision making. Therefore, this research provides a more accurate set of reference information for building space design based on occupant satisfaction and physical and mental health. The study methods and conclusions can be adopted to obtain additional real information from human brain signals, which can then be used to optimize architectural space design.

## 5. Future research and next steps

Due to a lack of comprehensive time-based correction and improvement mechanisms, traditional methods require long-term verification to evaluate whether space and environment design results produce the expected implementation effects. Human-building interaction reflects the actual effects buildings have on the human experience. It contains the basic elements of relatively complete and reliable information collection, analysis, synthesis, and integration of space form, and has the advantage of improving the reliability of architectural design results. Therefore, based on empirical research, the purpose of this study was to focus on the ongoing improvement of the built environment from the perspective of a harmonious symbiosis between human beings and built environment, with the goal of promoting occupants' physical and mental health. Through this study, a systematic and innovative building space quality evaluation and design optimization method was established to achieve the coordinated development of human beings, building spaces, and the environment.

This research revealed the correlation mechanism between building space information and human perceptual feedback. Future studies will focus on the development of algorithms for computer analysis and machine learning, formation of applications-oriented quantitative models, embedding of evidence-based laboratory work into the design process, and creation of innovative programming and software. The method demonstrated here can be used to develop mechanisms of physiological feedback and space scenes for occupants in medical, commercial, office, underground, and special environments, and produce effective feedback for design optimization. Future work on this topic will address the formation of an analytical paradigm for EEG data, testing of typical built environments, and provision of direct feedback for visualization platforms and applications. For example, in office spaces, by adjusting certain design elements, EEG rhythms can be stimulated to improve work efficiency. In commercial spaces, by changing spatial elements, EEG rhythms can be stimulated to improve consumers' mood. In underground and medical spaces, occupants' comfort and satisfaction can be improved through limited environmental factors, which may in the long term affect occupants' health.

## CRediT authorship contribution statement

**Junjie Li:** Conceptualization, Writing - original draft, Methodology, Visualization, Investigation, Writing - review & editing, Funding acquisition. **Yichun Jin:** Investigation, Data curation, Writing - review & editing, Formal analysis, Visualization. **Shuai Lu:** Software, Resources, Visualization. **Wei Wu:** Investigation, Software. **Pengfei Wang:** Investigation.

## Declaration of Competing Interest

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

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## References

[1] Y. Song, Technology and design: The design mode of paying attention to environment, World Architect. 07 (2015) 38–39.
[2] J.K. Day, D.E. Gunderson, Understanding high performance buildings: The link between occupant knowledge of passive design systems, corresponding behaviors, occupant comfort and environmental satisfaction, Build. Environ. 84 (01) (2015) 114–124.
[3] U.S. Green Building Council. LEED for New Construction, Version 4.0, 2014.
[4] J.J. McArthur, C. Powell, Health and wellness in commercial buildings: Systematic review of sustainable building rating systems and alignment with contemporary research, Build. Environ. 01 (2020) 106635.
[5] L. Xiaodong, S. Shu, Z. Zhihui, K. Xiangqin, An integrated environmental and health performance quantification model for pre-occupancy phase of buildings in China, Environ. Impact Assess. Rev. 63 (03) (2017) 1–11.
[6] Y. Song, J. Li, J. Wang, S. Hao, N. Zhu, Z. Lin, Multi-criteria approach to passive space design in buildings: Impact of courtyard spaces on public buildings in cold climates, Build. Environ. 89 (07) (2015) 295–307.
[7] J. Li, S. Lv, Q. Wang, Graphical visualization and analysis of indoor environmental performance: Impact of atrium spaces on public buildings in cold climates, Indoor Built Environ. 03 (2018) 331–347.
[8] J. Li, Y. Song, S. Lv, Q. Wang, Impact evaluation of indoor environmental performance of animate space in buildings, Build. Environ. 94 (12) (2015) 353–370.
[9] J. Kim, M. Kong, T. Hong, et al., Physiological response of building occupants based on their activity and the indoor environmental quality condition changes, Build. Environ. 145 (11) (2018) 96–103.
[10] Z. Zhang, Y. Zhang, A. Khan, Thermal comfort of people from two types of air-conditioned buildings: Evidence from chamber experiments, Build. Environ. 162 (09) (2019) 106287.
[11] X. Shan, E. Yang, J. Zhou, et al., Neural-signal electroencephalogram (EEG) methods to improve human-building interaction under different indoor air qualities, Energy Build. 197 (03) (2019) 188–195.
[12] X. Shan, E. Yang, J. Zhou, et al., Human-building interaction under various indoor temperatures through neural-signal electroencephalogram (EEG) methods, Build. Environ. 129 (08) (2018) 46–53.
[13] Y. Zhang, Research on the impact of indoor light environment on work efficiency, Chongqing University, Chongqing, 2014.
[14] Y. Choi, M. Kim, C. Chun, Effect of temperature on attention ability based on electroencephalogram measurements, Build. Environ. 147 (01) (2019) 299–304.
[15] A. Coburn, O. Kardan, H. Kotabe, et al., Psychological responses to natural patterns in architecture, J. Environ. Psychol. 62 (04) (2019) 133–145.
[16] V.K. Ojha, D. Griego, S. Kuliga, et al., Machine learning approaches to understanding the influence of urban environments on human physiological response, Inf. Sci. 474 (02) (2019) 154–169.
[17] P.O. Fanger. Fundamentals of thermal comfort: Advances in solar energy technology. 1988, (04): 3056-3061.
[18] L. Zampetti, M. Arnesano, G.M. Revel, Experimental testing of a system for the energy-efficient sub-zonal heating management in indoor environments based on PMV, Energy Build. 166 (05) (2018) 229–238.
[19] B. Cao, Q. Ouyang, Y. Zhu, L. Huang, H. Hu, G. Deng, Development of a multivariate regression model for overall satisfaction in public buildings based on field studies in Beijing and Shanghai, Build. Environ. 47 (01) (2012) 394–399.
[20] L. Huang, Y. Zhu, Q. Ouyang, B. Cao, A study on the effects of thermal, luminous, and acoustic environments on indoor environmental comfort in offices, Build. Environ. 49 (03) (2012) 304–309.
[21] J. Kim, T. Hong, M. Kong, Building occupants' psycho-physiological response to indoor climate and CO2 concentration changes in office buildings, Build. Environ. 169 (02) (2020) 106596.
[22] D.J. Hsu, Y.M. Sun, K.H. Chuang, Y.J. Juang, F.L. Chang, Effect of elevation change on work fatigue and physiological symptoms for high-rise building construction workers, Saf. Sci. 46 (5) (2008) 833–843, https://doi.org/10.1016/j.ssci.2007.01.011.
[23] X. Wang, D. Li, C.C. Menassa, Investigating the effect of indoor thermal environment on occupants' mental workload and task performance using electroencephalogram, Build. Environ. 158 (07) (2019) 120–132.

[24] M. Frontczak, S. Schiavon, J. Goins, E. Arens, H. Zhang, P. Wargocki, Quantitative relationships between occupant satisfaction and satisfaction aspects of indoor environmental quality and building design: Indoor environmental quality, Indoor Air 22 (2) (2012) 119–131.
[25] X. Chen, Z. Cui, L. Hao, Research on the methodology of evidence-based design based on VR Technology, China Illuminating Eng. J. 30 (02) (2019) 123–129.
[26] S. Yuan, H. Zhang, B. He, Y. Zhang, Research on visual perception and spatial behavior in tradtional Chinses villages based on a VR experiment: A case study in Xiamei and Chengcun, New Architect. 06 (2019) 36–40.
[27] M. Loyola, Influence of the availability of visual cues on the accurate perception of spatial dimensions in architectural virtual environments, Virtual Reality 22 (2018) 235–243.
[28] V. Abromavičius, A. Serackis, Eye and EEG activity markers for the visual comfort level of images, Biocybern. Biomed. Eng. 38 (04) (2018) 810–818.
[29] Z. Wang, W. Zhuang, Research on comment data for POE by perceptual evaluation SD method, New Architect. 04 (2019) 38–42.
[30] L. Yin, C. Zhang, Z. Cui, Experimental research on real-time acquisition and monitoring of wearable EEG based on TGAM module, Comput. Commun. 151 (01) (2020) 76–85.
[31] A. Mishra, B. Englitz, M.X. Cohen, EEG microstates as a continuous phenomenon, NeuroImage 208 (2020) 116454, https://doi.org/10.1016/j.neuroimage.2019.116454.
[32] R.J. Barry, F.M. De Blasio, J.S. Fogarty, Natural alpha frequency components in resting EEG and their relation to arousal, Clin. Neurophysiol. 131 (01) (2020) 205–212.
[33] C. Wei, L. Chen, Z. Song, EEG-based emotion recognition using simple recurrent units network and ensemble learning, Biomed. Signal Process. Control 58 (04) (2020) 101756.
[34] H. Chen, W. Chen, Y. Song, EEG characteristics of children with attention-deficit/hyperactivity disorder, Neuroscience 406 (05) (2019) 444–456.
[35] Y. Choi, M. Kim, C. Chun, Measurement of occupants' stress based on electroencephalograms (EEG) in twelve combined environments, Build. Environ. 88 (06) (2015) 65–72.
[36] D. Lai, X. Zhou, Q. Chen, Modelling dynamic thermal sensation of human subjects in outdoor environments, Energy Build. 149 (08) (2017) 16–25.
[37] A. Ploder, A. Eder. Semantic differential. International Encyclopedia of the Social & Behavioral Sciences (Second Ed.), 2015, 563-571.
[38] W. Zhuang, Theory of architectural programming: An approach to the methodology of design (in Chinese), Tsinghua University, Beijing, 1991, p. 12.
[39] B.M. McLaren, T. Gog, C. Ganoe, The efficiency of worked examples compared to erroneous examples, tutored problem solving, and problem solving in computer-based learning environments, Comput. Hum. Behav. 55 (02) (2016) 87–99.
[40] P.E. Turkeltaub, G.F. Eden, K.M. Jones, T.A. Zeffiro, Meta-analysis of the functional neuroanatomy of single-word reading: Method and validation, Neuroimage 16 (2002) 765–780.
[41] G.G. Brown, S.S. Kindermann, G.J. Siegle, E. Granholm, E.C. Wong, R.B. Buxton, Brain activation and pupil response during covert performance of the Stroop Color Word task, J. Int. Neuropsychol. Soc. 5 (1999) 308–319.
[42] Y. Huang, L. Su, Q. Ma, The Stroop effect: An activation likelihood estimation meta-analysis in healthy young adults, Neurosci. Lett. 716 (01) (2020) 134683.
[43] D.E. Nee, T.D. Wager, J. Jonides, Interference resolution: Insights from a meta-analysis of neuroimaging tasks, Cogn. Affect. Behav. Neurosci. 7 (2007) 1–17.
[44] A.D. Craig, How do you feel now? The anterior insula and human awareness, Nat. Rev. Neurosci. 10 (2009) 59–70.
[45] J. Toftum, D.P. Wyon, H. Svanekar, A. Lantner, Remote performance measurement (RPM): A new, internet-based method for the measurement of occupant performance in office buildings, Proc. Indoor Air (2005) 357–361.
[46] S. Sanei, J. Chambers, EEG Signal Processing, John Wiley & Sons, West Sussex, England, 2007.
[47] M. Gola, M. Magnuski, I. Szumska, A. Wróbel, EEG beta band activity is related to attention and attentional deficits in the visual performance of elderly subjects, Int. J. Psychophysiol. 89 (3) (2013) 334–341.
[48] M. Sterman, Sensorimotor,, EEG operant conditioning: Experimental and clinical effects, Pavlovian J. Biol. Sci.: Off. J. Pavlovian 12 (2) (1977) 63–92.
[49] C. Lee, J. Kwon, G. Kim, J. Hong, D. Shin, D. Lee, A study on EEG based concentration transmission and brain computer interface application, J. Instit. Electron. Eng. Korea 46 (2) (2009) 41–46.
[50] M.H. MacLean, K.M. Arnell, K.A. Cote, Resting EEG in alpha and beta bands predicts individual differences in attentional blink magnitude, Brain Cogn. 78 (3) (2012) 218–229.
[51] C.D. Katsis, N. Katertsidis, G. Ganiatsas, D.I. Fotiadis, Toward emotion recognition in car-racing drivers: A biosignal processing approach, IEEE Trans. Syst. Man. Cybern. A, Syst. Hum. 38 (3) (2008) 502–512.
[52] K.H. Kim, S.W. Bang, S.R. Kim, Emotion recognition system using short-term monitoring of physiological signals, Med. Biol. Eng. Comput. 42 (3) (2006) 419–427.
[53] E.T. Esfahani, V. Sundararajan, Using brain-computer interface to detect human satisfaction in human-robot interaction, Int. J. Human. Rob. 8 (1) (2011) 87–101.
[54] R.W. Picard, E. Vyzas, J. Healey, Toward machine emotional intelligence: Analysis of affective physiological state, IEEE Trans. Pattern Anal. Mach. Intell. 23 (10) (2001) 1175–1191.
[55] H. Jebelli, S. Hwang, S. Lee, EEG signal-processing framework to obtain high quality brain waves from an off-the-shelf wearable EEG device, J. Comput. Civ. Eng. 32 (1) (2018) 04017070.
[56] L.J. Trejo, K. Kubitz, R. Rosipal, R.L. Kochavi, L.D. Montgomery, EEG-based estimation and classification of mental fatigue, Psychology 6 (05) (2015) 572–589.
[57] K. Jurewicz, K. Paluch, E. Kublik, EEG-neurofeedback training of beta band (12–22 Hz) affects alpha and beta frequencies: A controlled study of a healthy population, Neuropsychologia 108 (01) (2018) 13–24.

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# Electroencephalographic Correlates of Sensorimotor Integration and Embodiment during the Appreciation of Virtual Architectural Environments

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Nowadays there is the hope that neuroscientific findings will contribute to the improvement of building design in order to create environments which satisfy man's demands. This can be achieved through the understanding of neurophysiological correlates of architectural perception. To this aim, the electroencephalographic (EEG) signals of 12 healthy subjects were recorded during the perception of three immersive virtual reality environments (VEs). Afterwards, participants were asked to describe their experience in terms of Familiarity, Novelty, Comfort, Pleasantness, Arousal, and Presence using a rating scale from 1 to 9. These perceptual dimensions are hypothesized to influence the pattern of cerebral spectral activity, while Presence is used to assess the realism of the virtual stimulation. Hence, the collected scores were used to analyze the Power Spectral Density (PSD) of the EEG for each behavioral dimension in the theta, alpha and mu bands by means of time-frequency analysis and topographic statistical maps. Analysis of Presence resulted in the activation of the frontal-midline theta, indicating the involvement of sensorimotor integration mechanisms when subjects expressed to feel more present in the VEs. Similar patterns also characterized the experience of familiar and comfortable VEs. In addition, pleasant VEs increased the theta power across visuomotor circuits and activated the alpha band in areas devoted to visuospatial exploration and processing of categorical spatial relations. Finally, the de-synchronization of the mu rhythm described the perception of pleasant and comfortable VEs, showing the involvement of left motor areas and embodied mechanisms for environment appreciation. Overall, these results show the possibility to measure EEG correlates of architectural perception involving the cerebral circuits of sensorimotor integration, spatial navigation, and embodiment. These observations can help testing architectural hypotheses in order to design environments matching the changing needs of humans.

**Keywords: electroencephalography, immersive virtual reality, presence, architecture, embodiment, sensorimotor integration, spatial navigation, affordances**

## INTRODUCTION

Despite increasing evidence of the influence physical features in the built environments have on our psychophysiological states (Stamps, 1999; Lindal and Hartig, 2013), systematic research on the cerebral networks activated by perception and appreciation of architectural spaces is still scarce. At the same time, there is a growing trend in architectural practice of employing the evidence-based insights for creating environments capable of satisfying the need for variety and improving people's psychological, biological and social lives. In this regard, the present study aims to illustrate the potential that neuroscientific findings have for describing the impact of architecture on people.

First of all, buildings have to respond to various functional requirements such as adequate lighting, heating, and cooling systems as well as public safety provisions. These functional aspects of architectural design are strongly supported by contemporary technological advances. However, the understanding of how the aesthetic perception of living environments affects people's cognitive and emotional states primarily relies on the architect's intuition and experience. In this context, available research provides good indications that personal sensory motor perception of the environment could play an important role in cognitive and emotional interactions within the environment itself. Most importantly, these attributes can now be evaluated from the neurophysiological point of view. Therefore, it becomes relevant to understand the human cerebral reactions produced by the perception of architecture. This claim is generally supported by different studies from various disciplines, including environmental psychology, behavioral research, and biophilic design.

More specifically, Appleton's habitat theory (Appleton, 1996) states that considering an environment as emotionally and aesthetically pleasing is indicative of its favorability to survival. In fact, since spatial features influence the activities and social interactions to be performed in a specific environment (i.e., sleeping in a bedroom or entertaining guests in a living room), architecture can affect cognitive and emotional states of inhabitants as well as their mood and productivity (Graham et al., 2015). These authors take into account different perceptual dimensions, highlighting the role of comfort as an important factor in both home and work environments in order to promote well-being and productivity. Additionally, architectural design can either limit or facilitate the social interactions and the dynamics that take place at home (Graham et al., 2015). Furthermore, studies show that the perception of different kinds of environments can have a beneficial impact on the observer's cognitive ability and task performance. For instance, the exploration of an environment can promote long-term potentiation in the hippocampus, improving memory encoding.

Although direct evidence of a link between exploration of environments and increased plasticity comes from studies on animals, such a link has been also found in humans. Indeed, an improvement of the recall of both allocentric spatial information (Plancher et al., 2013) and words (Schomaker et al., 2014), as well as memory encoding (Bunzeck and Düzel, 2006) was demonstrated when familiar items were presented during the active exploration of new environments.

In addition, evidence of the cerebral responses underpinning perceptual dimensions such as pleasantness is also found in studies on art appreciation, showing the activation of the motor system through embodied mechanisms, encompassing the simulation of actions, emotions, and corporeal sensations, which are also postulated to play an important role in the perception of architecture (Freedberg and Gallese, 2007). The idea of the involvement of non-overt bodily reactions in the perception and the experience of architectural spaces can be traced back from late nineteenth century "Einfühlung" theories. Such hypotheses suggest that the observation of architectural forms may lead to corporeal responses establishing a relationship between the aesthetic and emotional dimension, as well as bodily engagement with space (Mallgrave and Ikonomou, 1994). These assumptions have been validated by recent neuroscientific findings, highlighting the crucial role of sensorimotor areas in the appreciation of works of art (Kawabata and Zeki, 2004; Umilta' et al., 2012; Sbriscia-Fioretti et al., 2013). Freedberg and Gallese (2007) proposed a theoretical framework based on the role of embodied simulation and empathy in the aesthetic experience of art resulting in tactile sensations, implied gestures and actions. Additionally, the interaction with the built environment as well as its appreciation could also involve motivational and affective factors. In fact, the perception of visual artwork (Sbriscia-Fioretti et al., 2013) and environments characterized by curvilinear contours (Vartanian et al., 2013) activates reward circuits formed by medial orbitofrontal and anterior cingulate cortices (Vartanian and Goel, 2004). Moreover, observation of art or architecture may be accompanied by activations of neural networks regulating reward and judgment, suggesting the involvement of emotional, cognitive and contextual factors mediating aesthetic appreciation (Chatterjee and Vartanian, 2014).

However, very few neuroscientific studies have been conducted so far that investigate the modulation of the cerebral activity during perception of real-like architectural environments. One of the reasons for this lack of knowledge consists in a methodological gap. Concretely, there is a difficulty in reproducing the qualitative richness of architectural spaces in highly controlled environments such as a laboratory, allowing systematic neurophysiological investigation. However, a growing number of studies in psychology and neuroscience demonstrate that such difficulties can be surmounted using the Immersive Virtual Reality (IVR; Sanchez-Vives and Slater, 2005; Bohil et al., 2011). The IVR technologies create a high sensorial immersion within a fictive three dimensional scenario, inducing in the observer the sense of presence defined as the "sense of being in the virtual environment" (Slater and Wilbur, 1997) that is, a psychophysiological state which reproduces realistic behaviors and physiological responses as if the subject was experiencing a real-life situation (Diemer et al., 2015). Hence, by using the IVR it is possible to create highly controlled real-size architectural environments, allowing the measurement of reliable behavioral and neurophysiological indices.

The objective of this study is to investigate whether simple architectural scenarios are able to modify perception as well as to explore its corresponding cerebral activity. An IVR paradigm was used to highlight the neurophysiological features underpinning architectural perception by analyzing the electroencephalographic (EEG) and autonomic reactions elicited by the perception of highly immersive real-size Virtual Environments (VEs). With the working hypothesis that changing interior design features could activate the cerebral circuits involved in mechanisms of embodiment in different ways, we compared the spectral activity of the EEG using a set of subjective dimensions describing the perception of VEs such as Pleasantness, Novelty, Familiarity, Comfort, Arousal, and Presence. In addition, the hypothesis that architectural perception could involve cerebral circuits regulating reward and affective processes was also advanced basing on a broad literature on aesthetic judgments (for a review, see Chatterjee and Vartanian, 2014).

## MATERIALS AND METHODS

### Participants

Twelve healthy volunteers were involved in the study (five females; mean ± SD 26.8 ± 2.4). All subjects had normal or corrected-to-normal vision and were not familiar with the IVR experience. The study was approved by the ethics committee of Fondazione Santa Lucia, according to the ethical standards of the 1964 Declaration of Helsinki.

### Procedure

Three VEs were designed in real size (5 × 5 m) and tested using different interior designs. The first one represented an empty room (VE1), which was in turn equipped with a modern design (VE2) and then with cutting-edge furniture (VE3) as shown in **Figure 1**. They were designed using 3DS Max 2011 (Autodesk, Inc.) and implemented in XVR (http://www.vrmedia.it/en/xvr.html; Tecchia et al., 2010).

The VEs were presented by means of a CAVE automatic virtual environment system (3 × 3 × 2.5 m; Cruz-Neira et al., 1993) composed by three rear-projection screens for the walls and a down- projection screen for the floor, as illustrated in **Figure 2**. Viewsonic projectors (1024 × 768 pixels) displayed images on the screens through mirrors and an Nvidia 3d vision wireless glass provided the image of 3D graphics generated by the CAVE. An Intersense 900 ultrasonic head tracking system (6° of Freedom, DoF) was used to record in real time the subject's head position and orientation (with a frequency of 120 Hz) and thus to anchor the 3D images to his/her point of view. As a special feature of the CAVE system, the four 3D images were joined together so that subjects could not see the edges of the adjacent walls. Hence, the active stereo projection was perceived as a continuous virtual world. This setup enabled a high level of sensorial immersion so that the subject could feel herself/himself physically present in the VE (Sanchez-Vives and Slater, 2005).

Subjects sat on a chair placed in the middle of the CAVE and immersed in each VE for 4 min. VEs presentation was counterbalanced among subjects. Their task was (i) to visually explore the surrounding environment and, at the end of the exposure, (ii) to verbally express their judgment about the perceptual dimensions of Familiarity, Novelty, Comfort, Pleasantness, Arousal, and Presence using a 9-point rating scale (1, lowest score; 9, highest score). These items were arranged in two short questionnaires, as shown in **Table 1**, each related to perception and sense of presence induced by the VEs, respectively. The items used to measure the sense of Presence were adapted from Sanchez-Vives and Slater (Sanchez-Vives and Slater, 2005). Subjects had 2 min to answer the questionnaires before experiencing the next VE. The whole procedure lasted around 20 min during which the EEG and autonomic activity were continuously collected, as described in the following section.

At the beginning, each subject experienced a familiarization period (Slater et al., 2010; Tieri et al., 2015a,b) within an

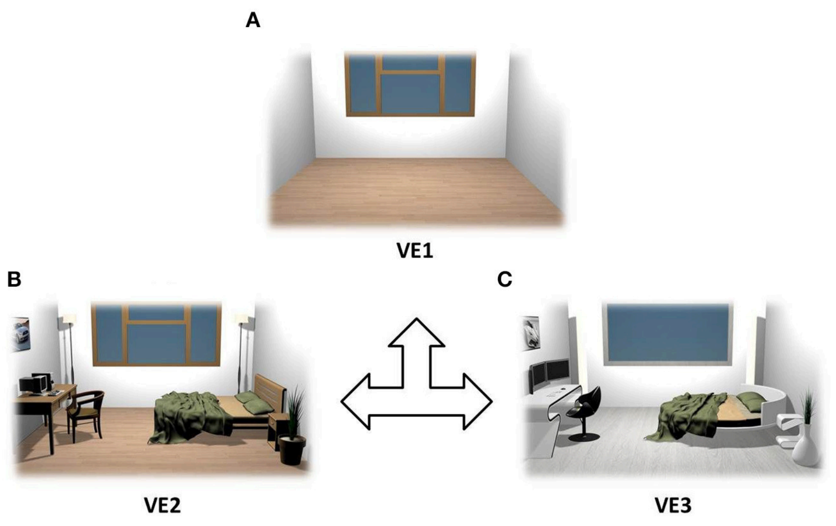


**FIGURE 1 | Rendering of the VEs that were used as stimuli.** VEs were counterbalanced across subjects: empty room **(A)**, modern furniture **(B)**, and cutting edge design **(C)**.

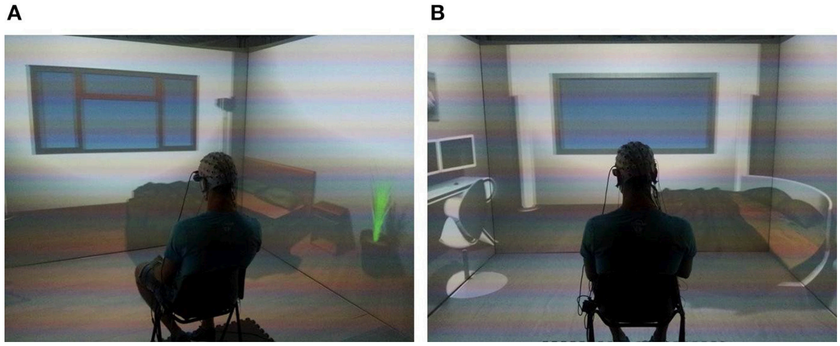

**FIGURE 2 | Virtual reality cave system setup.** It is possible to appreciate two rooms with different interior design: modern furniture **(A)** and cutting edge design **(B)**. The subject is placed in the middle of the cave, wearing the EEG cap, for the whole duration of the experiment.

**TABLE 1 | Items used to assess dimensions of perception and presence.**

| | Dimension | Item |
|---|---|---|
| Perception | Familiarity | How much did this VE remind you of environments in which you lived? |
| | Novelty | How much did this VE provide elements of novelty with respect to environments in which you lived? |
| | Comfort | How much did you feel at your ease during the perception of this VE? |
| | Pleasantness | How much did you like this VE? |
| | Arousal | How much did this VE arouse you? |
| Presence | | To what extent did you have the sense of being in the VE? |
| | | To what extent were there times during the experience when the VE became the reality for you and you almost forgot about the real world of the laboratory in which the whole experience was really taking place? |
| | | When you think about this experience, do you think of the VE more as images that you saw or more as somewhere that you visited? |

*Each dimension was evaluated according to a 9-point scoring scale (1, lowest; 9, highest).*

additional neutral VE that represented a generic laboratory setting composed by different objects including a chair, a desk, some computers, and books. Subjects were asked to look around the environment and verbally describe the virtual scenario. This preliminary phase ended when they reported to feel present in the environment (all participants experienced presence within 81.28 ± 37.62 s). The neurophysiological activity acquired during this phase was not used for further analysis.

## Behavioral Data Analysis

With the aim to investigate the relationship among each of the perceptual dimensions—Familiarity, Novelty, Comfort, Pleasantness, Arousal—the subjective behavioral scores were transformed in z-scores and then used to perform Pearson's correlation analysis (Bonferroni corrected due to multiple tests). Afterwards, two datasets for each perceptual dimension were created using the z-scores in order to identify and group VEs that had the highest and lowest scores, respectively, according to each subject. Therefore, positive ($z > 0$) scores represented VEs which were highly rated (e.g., High Pleasantness VEs) while negative ($z < 0$) scores were associated with lowly rated VEs (e.g., Low Pleasantness VEs). These z-scores were used to contrast the neurophysiological data: interiors rated with positive scores (e.g., High Pleasantness) were compared with the ones rated with negative scores (e.g., Low Pleasantness) for each perceptual dimension and presence.

According to this procedure, the analysis was driven by the subjective scores across all VEs instead of investigating the cerebral activity related to the perception of single VEs (see Vecchiato et al., 2010a, 2011b for a similar statistical approach). The subjective scores related to Presence were first averaged across the three items and then z-scored across stimuli. These were first used to separate VEs that induced either high or low presence and, subsequently, to group and contrast the neurophysiological activity. The data associated to $z = 0$ were not considered for the following analysis (6.48% of total scores).

## Electroencephalographic and Autonomic Signal Recording and Processing

The EEG activity was recorded by means of a portable 24-channel system (BEmicro, EBneuro, Italy). Nineteen electrodes were disposed according to the 10–20 I.S. The signals acquired at a sampling rate of 256 Hz with sensors impedances kept below 10 kΩ. Raw EEG traces were band pass filtered ($hp = 0.5$ Hz; $lp = 45$ Hz) and the Independent Component Analysis (ICA; Hyvärinen and Oja, 2000) was then applied to detect and remove components generated by eye movements and blinks. For this purpose, the infomax ICA algorithm was used, provided by EEGLAB (Delorme and Makeig, 2004). EEG data were extracted to take into account the perception of the three VEs (three stimuli per subject) and further segmented into 1-s epochs (240 epochs per stimulus defining the 4 min exposition). Muscular and environmental artifacts were detected and removed with a semi-automatic procedure based on two different criteria: threshold (traces which exceeded a threshold of ±80 μV were rejected) and gradient (traces in which the difference between two consecutive samples exceeded ±50 μV were rejected). Only artifact-free trials (92.72%) were considered for this analysis. The extra-cerebrally referred EEG signals were transformed by means of the Common Average Reference (CAR). Afterwards, the Power Spectral Density (PSD) was computed for each epoch according to the Welch method (Welch, 1967) with Hanning window in a Matlab environment (The MathWorks, Inc.). Individual Alpha Frequency (IAF) was calculated for each subject to perform time-frequency analysis according to individually defined bands and widths (Doppelmayr et al., 1998). Therefore, in this study the bands of interest were defined as theta, ranging from IAF × 0.4 to IAF × 0.8 Hz, alpha (IAF × 0.8, IAF × 1.2) Hz and mu (IAF, IAF × 1.2) Hz.

In all subjects we achieved an IAF = 10.54 ± 0.80 Hz. Then, the PSD was band averaged to obtain data structures comprising $T = 240$ time-frequency bins per EEG channel and subject, for the three frequency bands. The whole dataset was pooled according to the behavioral z-scores in order to contrast the positive against the negatively judged VEs. This comparison was performed for each perceptual dimension (Familiarity, Novelty, Comfort, Pleasantness, Arousal) and Presence. Hence, a PSD time-frequency series was obtained for each condition.

Autonomic activity, such as Electrodermal Activity (EDA) and Heart Rate (HR), was recorded by means of a NeXus-4 (Mindmedia, The Netherlands) system with a sampling rate of 256 Hz. Skin conductance was acquired by the constant voltage method (0.5 V). Ag-AgCl electrodes were attached to the palmar side of the middle phalanges of the second and third fingers of the participant's non-dominant hand with a Velcro fastener, following published procedures (Boucsein et al., 2012). In order to retrieve the tonic component of the skin conductance (Skin Conductance Level, SCL) the LEDAlab software was employed (Benedek and Kaernbach, 2010). Disposable Ag-AgCl electrodes, which were provided by the Mindmedia company, were applied to the subject's wrist to collect cardiac activity. The Pan-Tompkins algorithm was then used to calculate the HR (Pan and Tompkins, 1985). Both EDA and HR were analyzed to asses Presence.

## PSD Non-Linear Time-Frequency Analysis

In order to account for non-linear dynamics of the EEG elicited during the continuous perception of the VEs, a method was developed inspired by time-delay embedding procedures (Stam, 2005, 2006). The application of non-linear dynamics to electroencephalography, often referred to with the term "chaos theory" (Elbert et al., 1994), paved the way to a new perspective for the study of normal and disturbed brain function (Stam, 2003). In fact, non-linear dynamics studies of the EEG are applied in wide research domains ranging from resting to active mental states (Aftanas and Golocheikine, 2002; Tirsch et al., 2004, see Stam, 2005 for a review). The wide use of non-linear analysis of the EEG is justified by the fact that levels of synchronization of functional sources are not constant over time, but show peculiar fluctuations which have a scale-free character (Stam and de Bruin, 2004).

In this analysis, the *PSD* time-frequency bins were averaged according to a changing time-window depending on the values of its autocorrelation function. Specifically, in $x[n] = PSD_{b,ch}[n]$, *PSD* is the time series of spectral values defined for the frequency $b$ and channel $ch$. For each increasing $t_N$ time window of length $N$, with $N \in [1, T]$, the autocorrelation function was computed as:

$$R_{xx}[m] = R_{xx}[-m] = \sum_{n=1}^{N} x[n]\, x[n-m]$$

with $m \in [1\text{-}N, N\text{-}1]$. Here are considered only values of $R_{xx}$ with $m \geq 0$. At each iteration $t_N$, $L_N$ equals the length of the time window, after which the autocorrelation function of the time series dropped to 1/e of its maximum value (Stam, 2005). Then, the weighted average of the *PSD* for each $t_N$ was computed as:

$$PSD_w[t_N] = \frac{\sum_{n=1}^{L_N} x[n]\, w[n]}{\sum_{n=1}^{L_N} w[n]}$$

where $w_n$ are the selected $L_N$ larger coefficients of the autocorrelation function. This calculation was performed for each subject and condition. Afterwards, the subjective z-score of *PSDw* spectral values for each time bin was calculated, as similarly done with behavioral scores, to perform the mass univariate analysis described in the following paragraph.

## Statistical Mass Univariate Analysis

EEG features are typically analyzed via statistical methods on average activity in a priori windows. Mass univariate analyses were born thanks to the advances in computing power and statistics (Blair and Karniski, 1993). They consist of hundreds or thousands of statistical univariate tests, e.g., Student's *t*-test, which are applied to a large number of time points or cerebral locations accompanied by corrections for multiple comparisons. Such analyses are very useful when there is little a priori knowledge of effect locations or latencies, as well as to delineate effect boundaries. For instance, conducting statistical analysis on particular cerebral features such as average or peak amplitude does not take into account the whole time-series of observations and, therefore, cannot provide information about when and/or where an effect occurs (Dien and Santuzzi, 2005). This analysis can be applied to EEG, magnetoencephalographic (MEG), and functional Magnetic Resonance Imaging (fMRI) data, as reviewed in Groppe et al. (2011). Here, this methodology is applied to the z-scored *PSDw* time series in order to contrast the spectral activity for each perceptual dimension and presence. This is made using multiple Student's *t*-test (significance level of 0.05) and the False Discovery Rate (FDR) correction for multiple comparisons to minimize type I errors (Benjamini and Yekutieli, 2001; Vecchiato et al., 2010b).

In the following figures, statistical results provided by the mass univariate analysis are shown by means of raster diagrams. Average *t*-test results in specific time-windows are also summarized by means of scalp topographic maps.

# RESULTS

## Behavioral Results

In **Figure 3** there are several boxplots showing the z-score distributions of the judgments related to the adopted behavioral

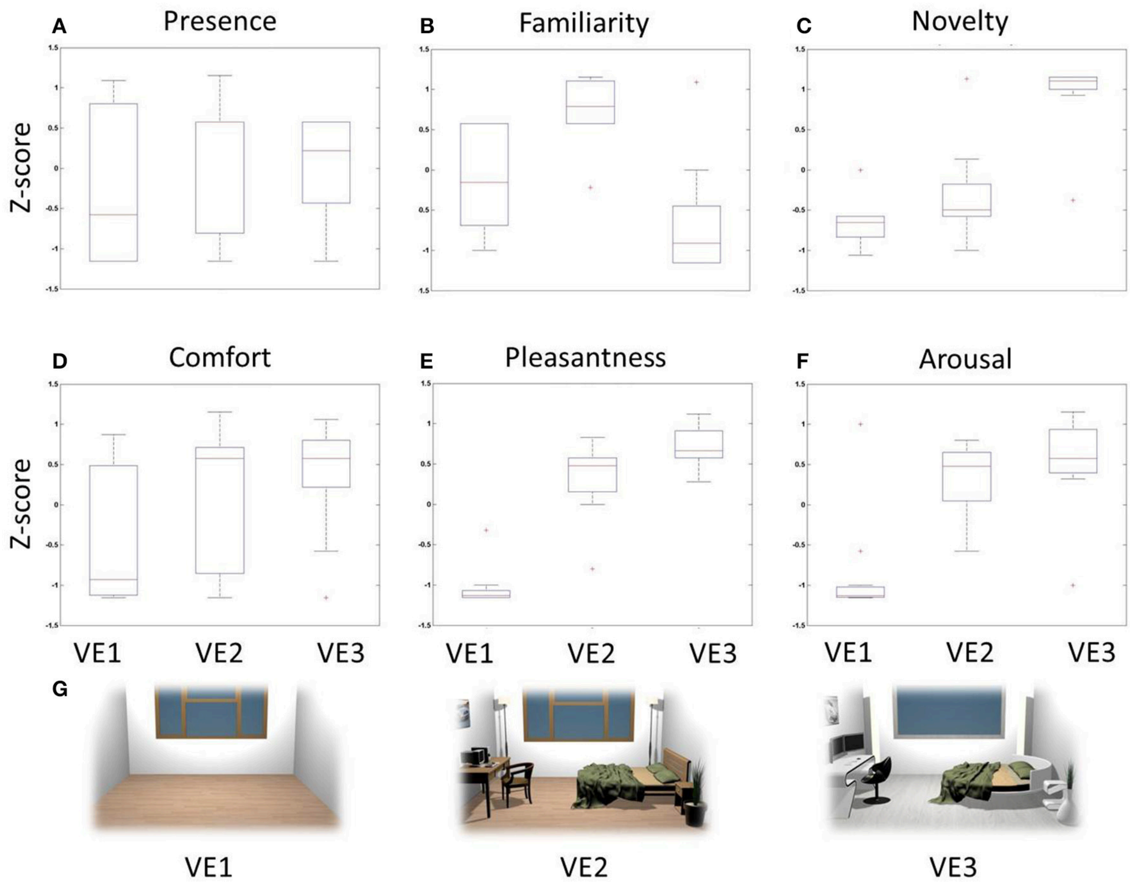


**FIGURE 3 | Z-score boxplots of behavioral judgments among VEs.** Each panel contains three boxplots related to the distribution of behavioral scores for VE1 (left), VE2 (center), and VE3 (right). On each box, the central mark is the median, the edges of the box are the 25th and 75th percentiles, the whiskers extend to the most extreme data points. Red crosses indicate outliers of the distribution. **(A)** Presence, **(B)** Familiarity, **(C)** Novelty, **(D)** Comfort, **(E)** Pleasantness, **(F)** Arousal, **(G)** Two-dimensional rendering of the three VEs designed and used for the stimulation.

dimensions. These graphs show that the VE judged highly familiar was the one characterized by modern furniture, while novelty dimension returned highest scores for the one with cutting-edge furniture. Instead, scores related to pleasantness and arousal revealed that subjects assigned the highest scores to interiors with objects in general, indistinctly of the kind of furniture.

The degree of correlation between perceptual dimensions is shown through the computation of the Pearson's coefficients (**Table 2**). In particular, judgments of Novelty were positively correlated with Pleasantness ($R = 0.68$, $p < 0.01$) and negatively with Familiarity ($R = -0.52$, $p < 0.01$). Judgments of Pleasantness were also positively correlated with Arousal ($R = 0.63$, $p < 0.01$). These results illustrate that the measured perceptual dimensions are characterized by a certain degree of correlation, which was investigated through cerebral data.

**TABLE 2 | Pearson's correlation coefficients among perceptual dimensions.**

| | Familiarity | Novelty | Comfort | Pleasantness | Arousal | Presence |
|---|---|---|---|---|---|---|
| Familiarity | 1 | *−0.52 | 0.08 | −0.06 | −0.07 | 0.11 |
| Novelty | | 1 | 0.27 | **0.68 | 0.31 | 0.18 |
| Comfort | | | 1 | 0.43 | 0.19 | 0.39 |
| Pleasantness | | | | 1 | **0.63 | 0.21 |
| Arousal | | | | | 1 | 0.12 |
| Presence | | | | | | 1 |

*$p < 0.05$, **$p < 0.01$, Bonferroni corrected for multiple comparisons.

## PSD Time-Frequency Pattern and Autonomic Variables of Presence

The z-scores computed for all behavioral dimensions were used to pool the whole *PSDw* dataset into groups for the mass univariate analysis. First, the z-scores related to the Presence dimension were used in order to (i) identify the autonomic and EEG correlates of presence and (ii) to investigate possible time windows showing most activation during the whole 4 min perception of the VEs. To this aim, HR, SCL and *PSDw* related to positive z-scores of Presence were grouped in the High Presence dataset (19 observations) while the HR and *PSDw* related to negative z-scores formed the Low Presence dataset (13 observations).

The HR waveforms were z-scored and averaged across subjects, as visible in **Figure 4A**. Here it is possible to appreciate that the largest difference between the two groups is within the time window $t_m = [60, 180]$ s comprising minutes 2 and 3, i.e., the central part of the experience in the VE. This result is highlighted in **Figure 4B**, where there are two boxplots showing the average z-score distributions, calculated on the interval $t_m$, for both High and Low Presence groups. The Student's $t$-test resulted in a significant increase of HR during the observation of VEs perceived with high presence ($t = 2.908$, $p = 0.007$).

Analysis performed on the SCL returned no significant difference ($t = -1.170, p = 0.252$).

The *PSDw* datasets were contrasted by computing multiple $t$-test ($p < 0.05$, FDR corrected). Such calculation was performed separately for each frequency band of interest. In **Figure 5** are represented the results of the mass univariate analysis in the theta band that was used to inspect cerebral areas involved in assessing the level of presence (Sanchez-Vives and Slater, 2005; Slobounov et al., 2015).

In **Figure 5A** the statistically significant increase of activation related to High Presence condition is highlighted in red, while the color blue represents Low Presence. This result shows that VEs perceived with high presence elicited a larger amount of theta power across frontal (Fp1, Fp2, Fz) and left temporal (T7) scalp sites, which was mainly found during the central part of the VE experience. This evidence is summarized in **Figure 5B**, which shows an average topographic map of $t$-values computed within the time window $t_m$. Again, red color highlights an increase of theta activity across frontal and left temporal locations ($t_{\text{mean}} > 2$). The analysis of alpha and mu band revealed a few seconds of significant activations at frontal and central sites (**Figures 5B,C**) which, on average, did not result in a sustained activity (**Figures 5E,F**).

## PSD Time-Frequency Patterns of Perceptual Dimensions

A similar analysis was performed to contrast the perceptual dimensions of Familiarity, Comfort, Pleasantness, Arousal, and Novelty.

The perceptual z-scores of Familiarity were divided into positive and negative scores to compare the *PSDw* between High Familiarity condition (z-scores $> 0$, 17 observations) with Low Familiarity condition (z-scores $< 0$, 18 observations), respectively. The results of these comparisons are shown in **Figure 6** in which raster diagrams depict the significant increase of spectral activity in the different bands of interest, second by second, as investigated by the mass univariate analysis. In this case, in the middle time window $t_m$ (i.e., the central part of the VE perception as highlighted by the dotted black box) there is an increase of theta activity at electrodes Fz and Pz, related to High Familiarity condition (**Figure 6A**). This pattern of activation is also visible through a topographic map which shows mainly the frontal rhythm with $t_{\text{mean}} > 2$ (**Figure 6D**). The raster diagrams of the alpha (**Figures 6B,E**) and mu (**Figures 6C,F**) bands do not provide any particularly sustained activation in the Familiarity condition.

The mass univariate analysis was then performed for the perceptual dimension of Comfort. As described above, in this condition the perceptual z-scores of Comfort were used to divide the *PSDw* dataset into two groups: High Comfort (z-scores $> 0$, 19 observations) and Low Comfort (z-scores $< 0$, 13 observations) undergoing the multiple $t$-tests. The results are shown in **Figure 7**, which depicts the raster diagrams for the bands of interest (**Figures 7A–C**), as well as their corresponding average topographic maps (**Figures 7D–F**). An increase of theta activity across the frontal midline (Fz and Fp1) associated to the High Comfort condition is visible from the raster diagram and the average scalp map within the time-window $t_m$. Although the alpha band shows significant de-synchronization for the same condition across frontal sites, the average map computed

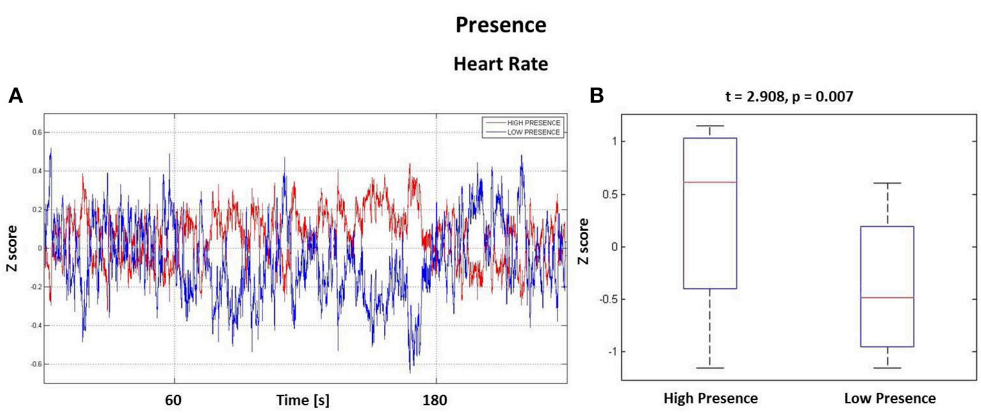


**FIGURE 4 | Results from the Heart Rate analysis. (A)** HR waveforms for the High Presence (red) and Low Presence (blue) conditions. Vertical grid highlights the time window $t_m$, the central part of experience, where the highest difference was found. **(B)** Boxplots showing the z-score distributions of High and Low Presence conditions computed in the time interval $t_m$. On each box, the central mark is the median, the edges of the box are the 25th and 75th percentiles, the whiskers extend to the most extreme data points. Difference is significant with $t = 2.908$ and $p = 0.007$.

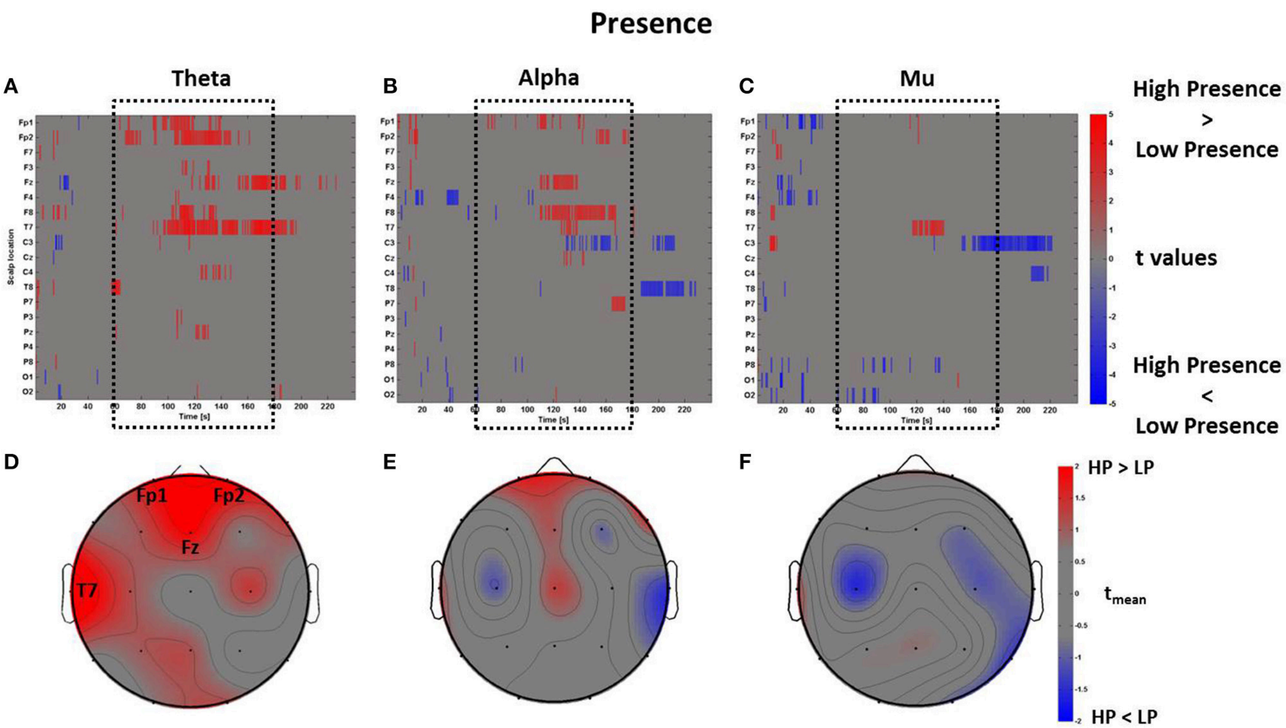


**FIGURE 5 | Time-frequency patterns of PSD for Presence. (A–C)** Raster diagram showing in red (blue) significant increase (decrease) of $t$-values for the EEG activity related to the perception of VEs with High Presence (Low Presence) in theta **(A)**, alpha **(B)**, and mu **(C)** bands. Gray color indicates no statistically significant difference ($p < 0.05$, FDR corrected). The dotted black box indicates the time window with most of activations. **(D–F)** Scalp topographic map of average $t$-values for theta **(D)**, alpha **(E)**, and mu **(F)** bands computed in the time window $t_m$ of VE experience. Black labels indicate the scalp sites which show $t_{mean} > 2$.

within the interval $t_m$ does not reveal any locations with $|t_{mean}| > 2$. Instead, the analysis computed in the mu band returned significant de-synchronization across left central (C3) and frontal (F3) electrodes, as visible by the scalp map presenting $|t_{mean}| > 2$.

By using the perceptual z-scores of Pleasantness, the *PSDw* dataset was divided into two groups associated with High Pleasantness (z-scores > 0, 22 observations) and Low Pleasantness (z-scores < 0, 13 observations) respectively. The results of the mass univariate analysis are reported in **Figure 8**, **Figures 8A–C** show the raster diagrams of the mass univariate analysis, while **Figures 8D–F** depict the average topographic map of $t$-values within the time window $t_m$ of VEs perception. **Figure 8A** emphasizes a wide increase of theta activity across occipito-parietal (P7, Pz, P4, P8, O1, O2) and frontal (F3, Fp2, F8) areas for the High Pleasantness condition. Instead, **Figures 8B,C** show the de-synchronization of the alpha band related to left frontal (F3) and parietal areas (P3, Pz) as well as a wide suppression of the mu rhythm across parietal (P3, Pz, P4) and left central (C3, Cz) regions. For the Pleasantness condition, cerebral activations exceeded the central part of the VE experience and seemed to accompany the subject until the end of the VEs experience. These results are also visible in the average topographic maps (**Figures 8D,E**).

The same mass univariate analysis and average topographic maps were performed for the perceptual dimensions of Arousal and Novelty. The results for Arousal are highly correlated with the ones regarding Pleasantness, as visible in **Figure 9**. In fact, the Pearson's coefficients were calculated between the distributions of average $t$-values within the time window $t_m$ summarizing the spectral activity of these two dimensions. The results show that the average *PSDw* of Arousal and Pleasantness are positively correlated in all bands (theta: $R = 0.93$, $p < 0.01$; alpha: $R = 0.94$, $p < 0.01$; mu: $R = 0.90$, $p < 0.01$. Bonferroni corrected).

In line with this result, we report another positive correlation between the spectral values related to the perceptual dimensions of Pleasantness and Novelty specifically in theta ($R = 0.76$, $p < 0.01$) and alpha ($R = 0.68$, $p < 0.01$) bands, even though the average topographical t maps of Novelty did not reveal average values of $|t_{mean}| > 2$ (**Figure 10**).

## DISCUSSION

In this study, the electroencephalographic activation underpinning the perception of VEs with different architectural appearances were investigated testing the hypothesis that variations in the virtually presented interiors could activate different cerebral circuits involved in mechanisms of embodiment. For this purpose, the EEG and autonomic activity were recorded during the visual exploration of three VEs. Each environment was designed with the intention to elicit different opinions on the perceptual dimensions of Pleasantness, Novelty, Familiarity, Comfort, and Arousal. Concretely, each

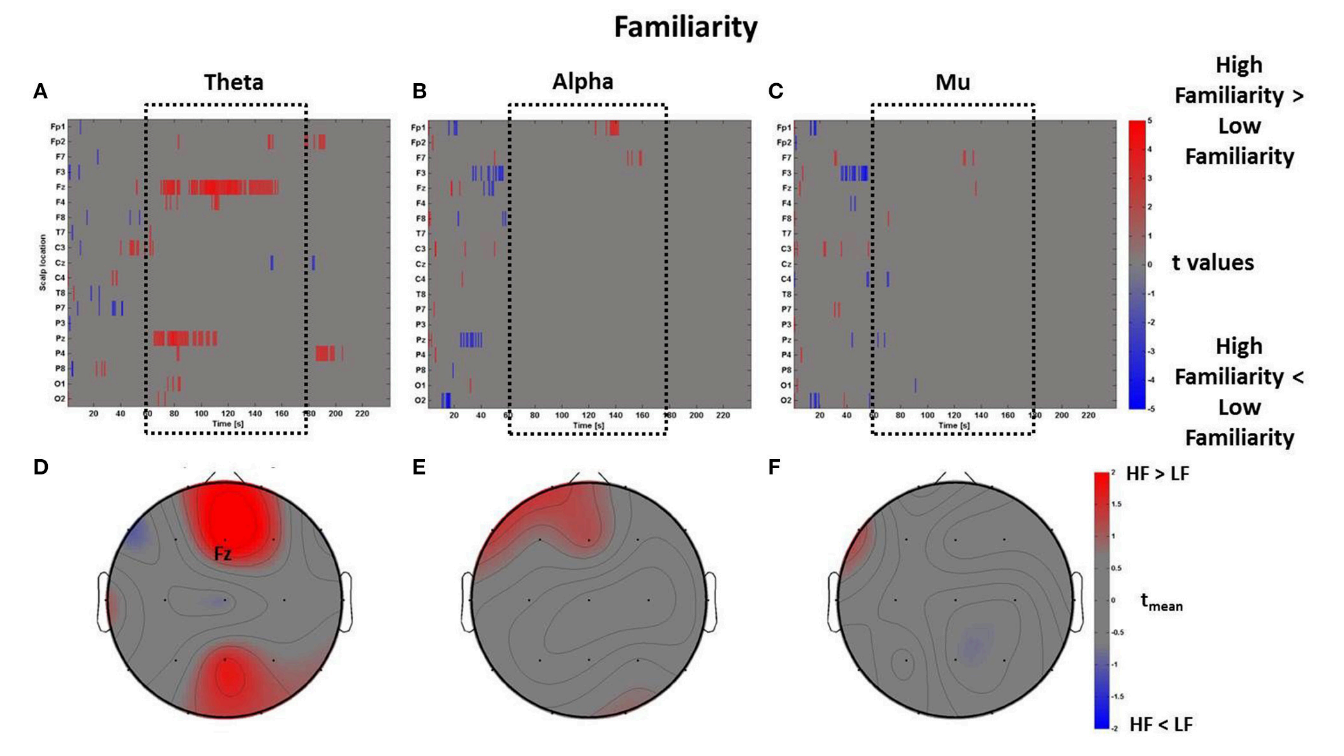


**FIGURE 6 | Time-frequency patterns of PSD for Familiarity. (A–C)** Raster diagram showing in red (blue) significant increase (decrease) of *t*-values for the EEG activity related to the perception of VEs with High Familiarity (Low Familiarity) in theta **(A)**, alpha **(B)**, and mu **(C)** bands. Gray color indicates no statistically significant difference ($p < 0.05$, FDR corrected). The dotted black box indicates the time window related to the middle part of VE experience. **(D–F)** Scalp topographic maps of average *t*-values for the theta **(D)**, alpha **(E)**, and mu **(F)** bands computed in the time window $t_m$ of VE experience. Black labels indicate the scalp sites which show $|t_{mean}| > 2$.

perceptual dimension was investigated by contrasting the cerebral activity related to the visual exploration of VEs with higher scores against the one of the VEs with lower scores. In order to select the most relevant time window of exposition, the neurophysiological data regarding the dimension of Presence were analyzed, highlighting the cerebral areas involved during this phenomenon and its specific temporal interval of interest.

Specifically, VEs judged with higher Presence scores revealed the involvement of frontal midline theta power. Similar activations were also found during the perception of familiar and comfortable VEs. Statistical comparisons related to the perceptual dimension of Pleasantness returned a complex pattern of activation in the analyzed bands. In particular, the theta band was characterized by a spread enhancement of activity across occipito-parietal and frontal networks, whereas the alpha band returned a de-synchronization of left parietal and frontal sites. Finally, the perception of both highly pleasant and comfortable VEs showed a de-synchronization of the mu rhythm mostly located in the left hemisphere. A detailed discussion of the aforementioned results is presented in the following sections.

## Sense of Presence and Sensorimotor Integration

IVR is a powerful tool for the investigation of the complex human behaviors during the natural interaction with the external world due to its capacity to represent real-life events and situations in highly controlled computer-generated environments (Tarr and Warren, 2002; Sanchez-Vives and Slater, 2005; Bohil et al., 2011; Dombeck and Reiser, 2012). The experience of IVR can elicit the illusory sensation of being physically present in the VE, this sensation is defined as sense of presence (Slater and Wilbur, 1997; Witmer and Singer, 1998; Diemer et al., 2015). The sense of presence leads to behavioral and neurophysiological reactions corresponding to real-life experience (Slater, 1999; Sanchez-Vives and Slater, 2005; Parsons and Rizzo, 2008). The intensity of these reactions depends on the number and range of the participant's sensory and motor channels connected to the virtual environment through different technological devices (Slater, 1999). For this purpose the VEs were recreated using a CAVE system which provides a high degree of sensorial immersion in the virtual world (Cruz-Neira et al., 1993).

The data show that the designed VEs were able to induce various degrees of presence, as revealed by the adopted questionnaire (Sanchez-Vives and Slater, 2005; Parsons and Rizzo, 2008; **Figure 3A**). Evidence led us to assess the cerebral pattern and autonomic activation underpinning the sense of presence and, accordingly, to consider the time interval characterized by the increase of frontal midline theta activity as the most significant for the tested architectural experience.

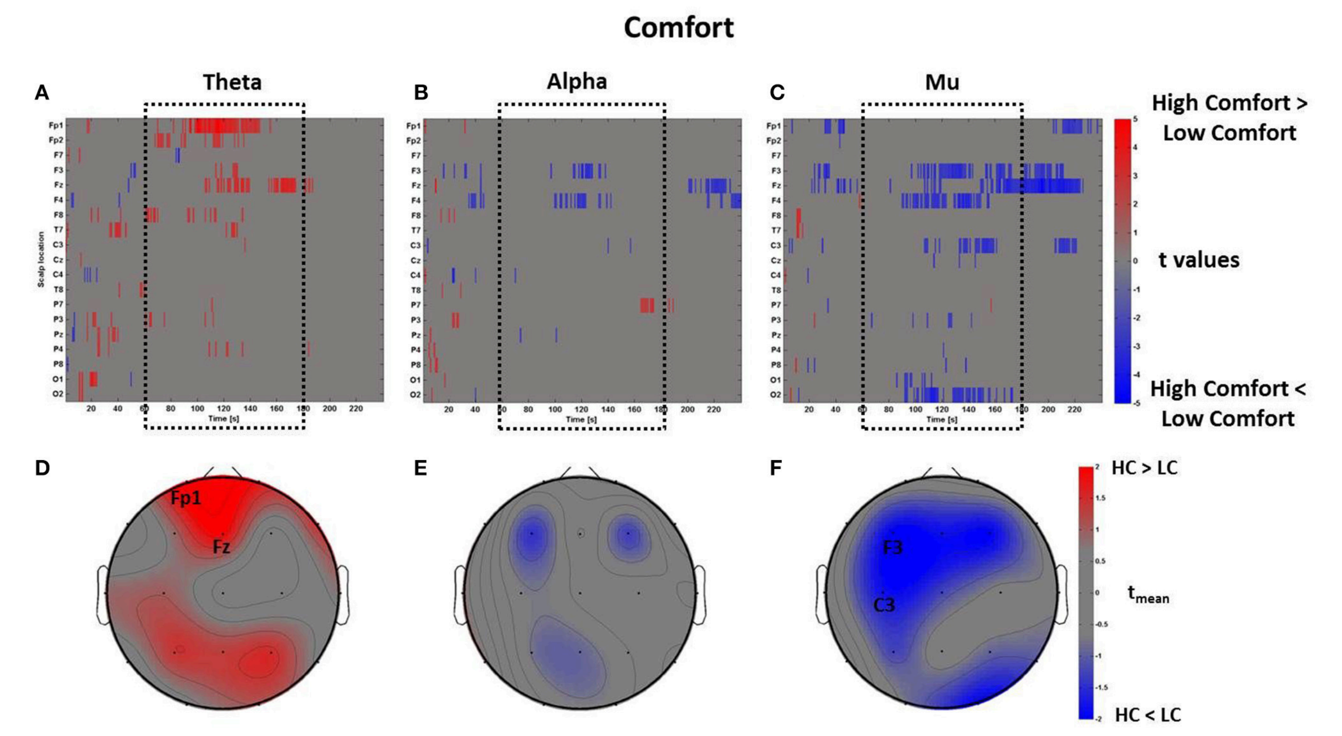


**FIGURE 7 | Time-frequency patterns of PSD for Comfort. (A–C)** Raster diagram showing in red (blue) significant increase (decrease) of *t*-values for the EEG activity related to the perception of VEs with High Comfort (Low Comfort) in theta **(A)**, alpha **(B)**, and mu **(C)** bands. Gray color indicates no statistically significant difference ($p < 0.05$, FDR corrected). The dotted black box indicates the time window related to the middle part of VE experience. **(D–F)** Scalp topographic maps of average *t*-values for the theta **(D)**, alpha **(E)**, and mu **(F)** bands computed in the time window $t_m$ of VE experience. Black labels indicate the scalp sites which show $|t_{mean}| > 2$.

Other studies also report significant correlations between presence and emotion (Baños et al., 2008), suggesting that a higher sense of presence could favor perception of emotional states. Similarly, physiological studies on the autonomous system report an increase of heart rate as a quantitative measure of Presence (Meehan et al., 2005), an observation which was also found in the present study. Based on the EEG data analysis, the cerebral areas which were mostly involved in the evaluation of presence were the frontal and orbitofrontal areas as well as the left temporal region. Specifically, an increase of theta activity was reported across these sites during the perception of VEs rated with High Presence scores. Similar results were also reported by two recent works on spatial navigation tasks using virtual reality. In particular, Slobounov and colleagues illustrate that during the state of presence in immersive 3D scenario subjects showed an enhancement of frontal midline theta (FM-theta) correlated with the success rate in a spatial navigation task, especially during the route encoding. This theta activity was considered to be a reflection of action monitoring, cognitive control and learning (Slobounov et al., 2015). Similarly, Kober and Neuper (2011) report an increase of FM-theta during the processing of familiar spatial cues. Both studies support the sensorimotor integration hypothesis which assigns to theta oscillations the role of coordinating the sensory information with a motor plan to direct wayfinding behavior toward known goal locations (Bland and Oddie, 2001; Caplan et al., 2003). Other studies also report a correlation of FM-theta with hippocampal theta activity during spatial navigation tasks in VEs (Caplan et al., 2003; Ekstrom et al., 2005), although the connection between theta cortical activity and hippocampus is still questioned (Mitchell et al., 2008).

Fronto-central theta rhythms are also increased during meditation and states of internalized attention (Aftanas and Golocheikine, 2001; Baijal and Srinivasan, 2009). Furthermore, theta band power increases with task demands and could be related to orienting (Dietl et al., 1999), memory (Klimesch, 1999), and affective processing (Sammler et al., 2007; Vecchiato et al., 2011a). This cerebral feature also appears during the state of concentration in mental and meditative tasks reflecting focused attentional processing and could be correlated with autonomous activity (Kubota et al., 2001). Therefore, the sense of presence could elicit mechanisms underlying sensorimotor integration as well as cerebral networks regulating focused attention, as reported in this study.

In addition, FM-theta was not only elicited during the experience of presence but also during the visuospatial exploration of more familiar, comfortable and pleasant environments. These findings may reflect recruitment of theta oscillations in focused attention, memory and positive emotional experience mechanisms associated with the exploration of VEs. Therefore, the recognition of familiar features in the environment, as well as the perception of comfort, could

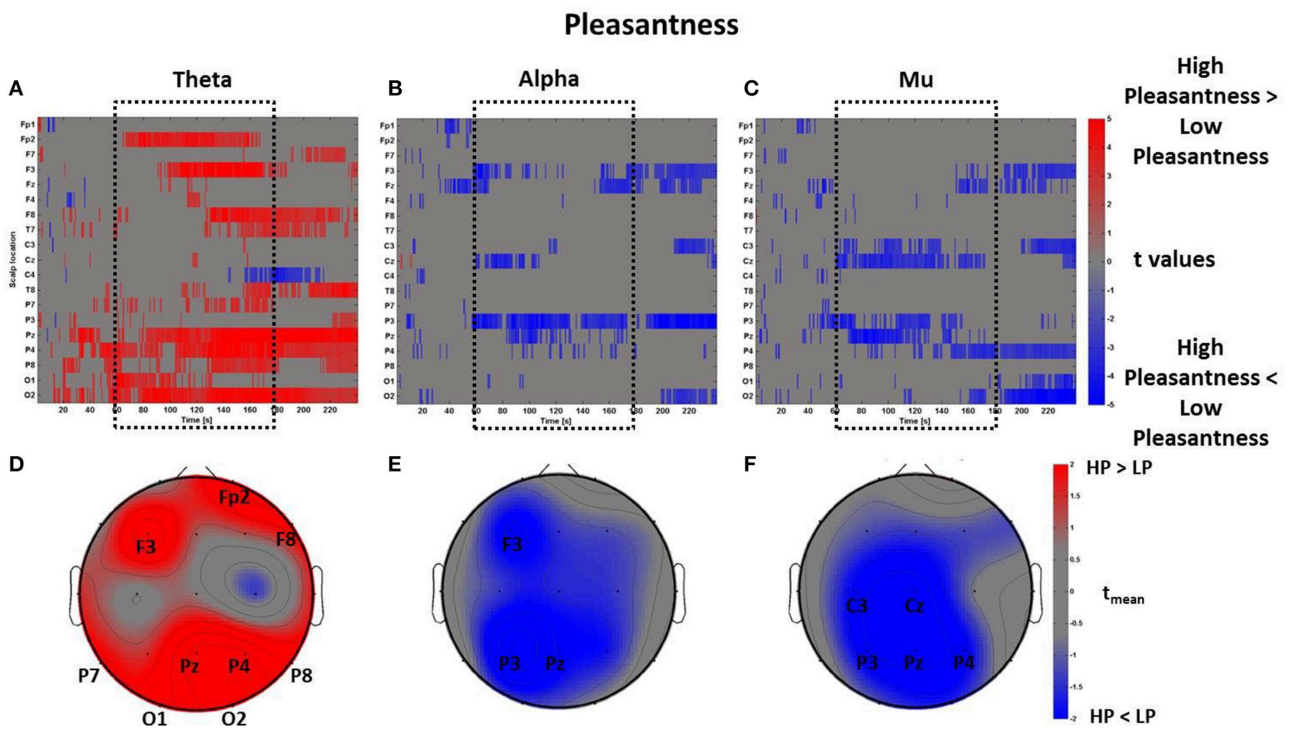


**FIGURE 8 | Time-frequency patterns of PSD for Pleasantness. (A–C)** Raster diagram showing in red (blue) significant increase (decrease) of *t*-values for the theta activity related to the perception of VEs with High Pleasantness (Low Pleasantness) in theta **(A)**, alpha **(B)**, and mu **(C)** bands. Gray color indicates no statistically significant difference ($p < 0.05$, FDR corrected). The dotted black box indicates the time window related to the middle part of VE experience. **(D–F)** Scalp topographic maps of average *t*-values for the theta **(D)**, alpha **(E)**, and mu **(F)** bands computed in the time window $t_m$ of VE experience. Black labels indicate the scalp sites which show $|t_{mean}| > 2$.

activate those cerebral circuits involved in internalized attention, relaxation and hence favor sensorimotor integration in space.

Overall, these results show that the discussed cerebral activations are common to the dimensions of Presence, Familiarity and Comfort, all showing an increase of theta frontal activity. However, an additional region was characterized by Presence only, which is the left temporal site. In their review, Jäncke and colleagues report the activation of a wide fronto-parietal network when participants reported a strong sense of presence in a virtual roller coaster scenario (Jäncke et al., 2009). Interestingly, these authors reported a difference between patterns of effective connectivity in adolescents and children. They attributed this finding to the prefrontal cortex which is not fully matured in children. Also, children are able to engage multi-sensory integration areas such as the temporo-parietal junction (TPJ) which is known to be a key area for studying self-location, i.e., the ability to place and experience oneself in the physical space (Aglioti and Candidi, 2011). TPJ is a cerebral region processing the body space proprioception and bodily awareness integrating signals coming from the body. This cortical area is involved in mental tasks where self-relocation is required, such as transcending body-related sensorimotor experiences usually occurring during meditative states (Urgesi et al., 2010). In particular, Ionta and colleagues reveal that multisensory integration in TPJ reflects the feeling of being an entity localized at a position in space, allowing the perception of the world from this perspective (Ionta et al., 2011).

An additional interpretation for this finding could be to connect the activation of the left temporal lobe with functions of visuomotor coordination and motor representation. Tankus and Fried (Tankus and Fried, 2012) discovered two neural populations in the human temporal-lobe activated differently during a motor and a visuomotor task, respectively. The second group of neurons, connected with the parahippocampal gyrus, had already been demonstrated to respond to visual motion (Sato and Nakamura, 2003) as well as to the observation of paintings reproducing landscapes (Kawabata and Zeki, 2004; Yue et al., 2007). It is known that images depicting environments activate the parahippocampal place area (PPA), an association area which codes place-related information and mediates contextual association with the environment (Epstein and Kanwisher, 1998; Bar, 2004). In fact, this area might not have been elicited in the above mentioned virtual roller coaster experiment because it was made of non-static movement scenes (Jäncke et al., 2009). Hence, these results seem to support the view that PPA could play a role in the cerebral circuit of presence.

## Aesthetic Experience

The pattern of cerebral activations related to High Pleasantness returned increased EEG power in all the investigated frequency

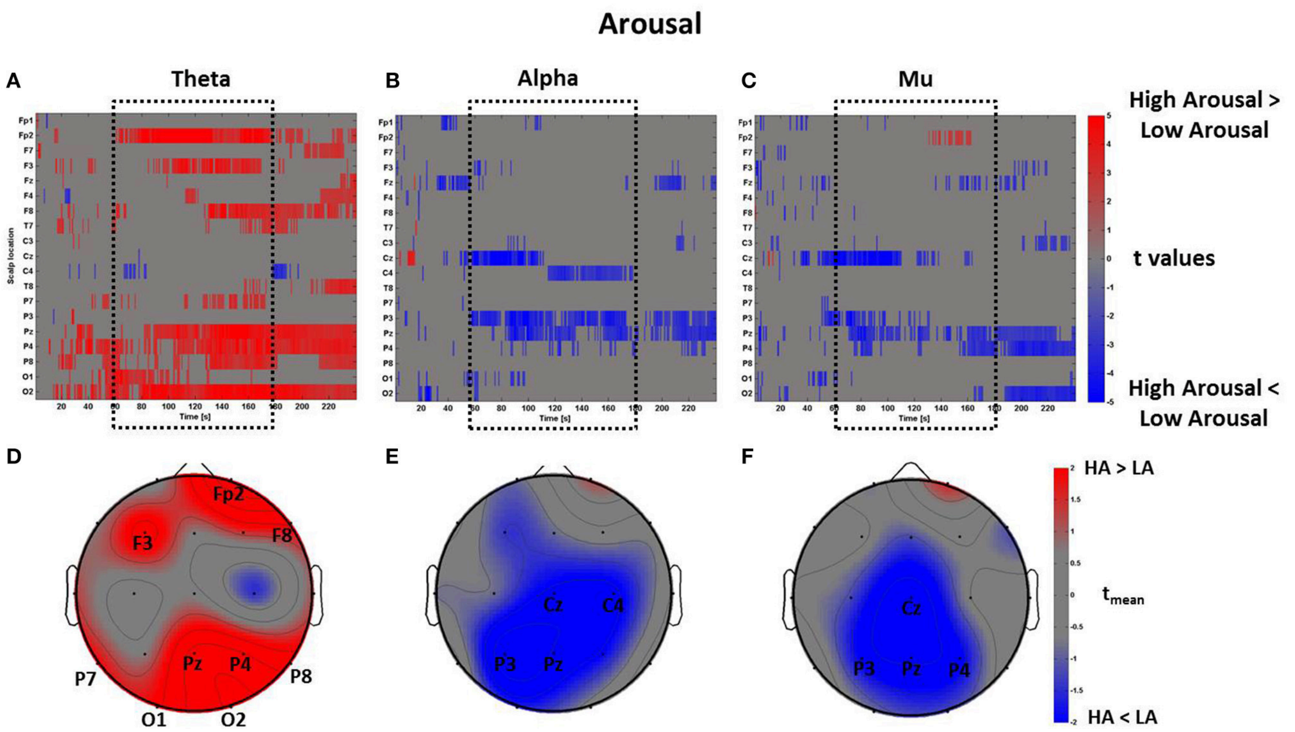


**FIGURE 9 | Time-frequency patterns of PSD for Arousal. (A–C)** Raster diagram showing in red (blue) significant increase (decrease) of *t*-values for the theta activity related to the perception of VEs with High Arousal (Low Arousal) in theta **(A)**, alpha **(B)**, and mu **(C)** bands. Gray color indicates no statistically significant difference ($p < 0.05$, FDR corrected). The dotted black box indicates the time window related to the middle part of VE experience. **(D–F)** Scalp topographic maps of average *t*-values for the theta **(D)**, alpha **(E)**, and mu **(F)** bands computed in the time window $t_m$ of VE experience. Black labels indicate the scalp sites which show $|t_{mean}| > 2$.

bands. Specifically, the perception of High Pleasantness environments activated not only mechanisms related to action planning but also to the sensory visual areas and frontal regions. According to a recent theoretical and experimental framework, aesthetic experience may involve the interaction of a neural systems' triad formed by the sensory-motor, the emotion-evaluation and the meaning-knowledge circuits (Chatterjee and Vartanian, 2014). Therefore, this perspective unifies both the sensory (e.g., pleasantness is positively correlated with the activation of sensory areas; Zeki, 1999) and the conceptual (e.g., pleasantness is positively correlated with the activation of frontal regions mediating concepts; Cela-Conde et al., 2004) hypotheses. In this regard, a recent study conducted by Thakral and colleagues show the activation of both visual and frontal cortices thus supporting sensory and conceptual hypotheses of aesthetic experience (Thakral et al., 2012). More specifically, these authors disentangle the response of the visual areas elicited by the observation of motion pictures from the frontal activity elicited by the observation of pleasant images. Their results provide evidence that motion experience is associated with activity in motion processing regions, while the experience of pleasantness is associated with the anterior prefrontal cortex. However, these two processes seem to interact in the same window of activation to engender the aesthetic experience (Lorteije et al., 2006).

Similarly, the results obtained in this study show an increase in the theta band in occipital, frontal and orbito-frontal regions during the perception of highly pleasant VEs. **Figure 3** illustrates that the furnished virtual rooms account for the "High Pleasantness" condition while the empty virtual room was evaluated as "Low Pleasantness." Accordingly, it might be reasonable to argue that the activity of the cerebral areas accounting for the amount of potential motion is generated by the possibility to interact and move around the objects located inside the virtual rooms. The activation of occipital areas had already been shown through the comparison of pictures with implied motion against the ones with non-implied motion (Lorteije et al., 2006). Other paradigms investigating the multisensory perception of objects in motion (Senkowski et al., 2007) and the processing of coherent meaningful objects (Vanni et al., 1997) have achieved the same results.

At the same time, the activity of the frontal lobe during perception of pleasantness is caused by the conceptual content of the stimulation as already reported in research papers (Cela-Conde et al., 2004; Ishizu and Zeki, 2011), meta-analysis (Kühn and Gallinat, 2012), and review (Chatterjee and Vartanian, 2014).

The activity of the parietal cortex, as indicated by the present results, could reflect the integration of multisensory information from different sensory modalities to form a coherent multimodal representation of space, which is coded in a body-centered

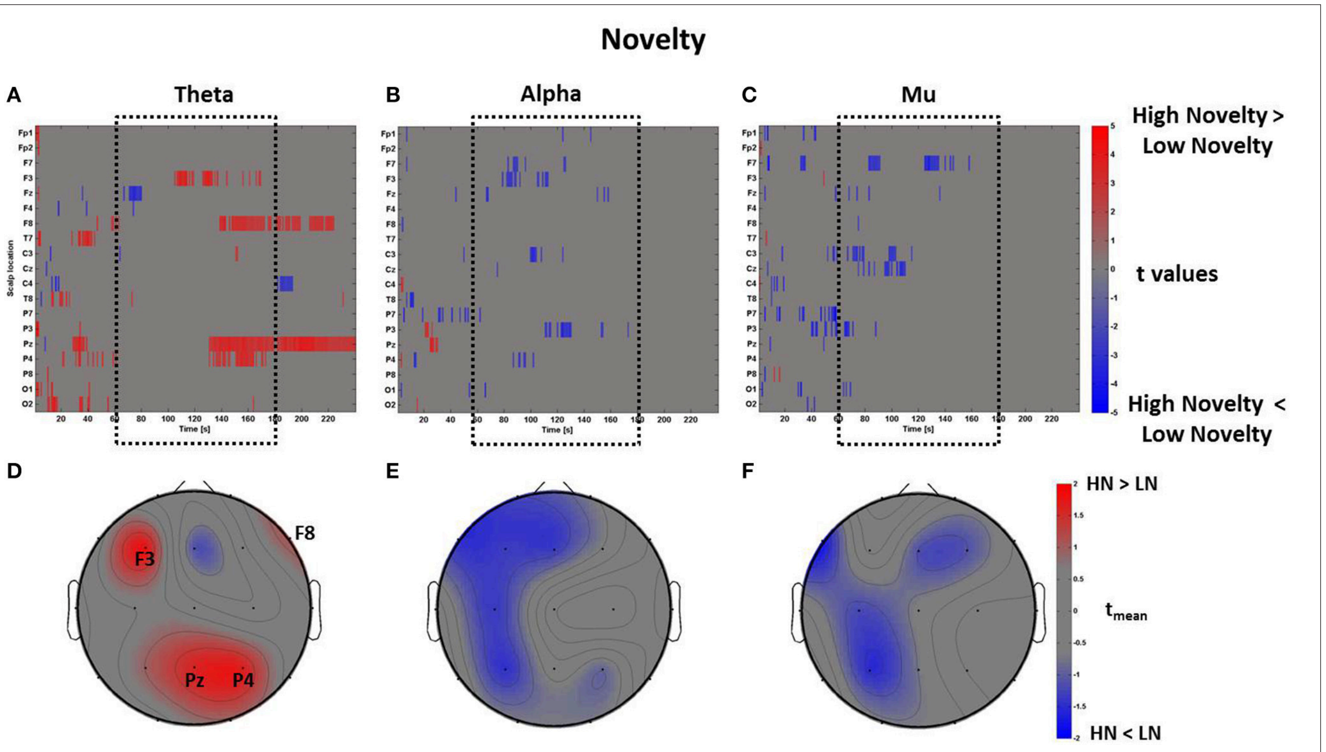


**FIGURE 10 | Time-frequency patterns of PSD for Novelty. (A–C)** Raster diagram showing in red (blue) significant increase (decrease) of *t*-values for the theta activity related to the perception of VEs with High Novelty (Low Novelty) in theta **(A)**, alpha **(B)**, and mu **(C)** bands. Gray color indicates no statistically significant difference ($p < 0.05$, FDR corrected). The dotted black box indicates the time window related to the middle part of VE experience. **(D–F)** Scalp topographic maps of average *t*-values for the theta **(D)**, alpha **(E)**, and mu **(F)** bands computed in the time window $t_m$ of VE experience. Black labels indicate the scalp sites which show $|t_{mean}| > 2$.

reference frame (evidence already reported in a VR study, Jäncke et al., 2009). The integration of multisensory cues around the body in the peripersonal space serves to map the position of objects in the surrounding environment in terms of one's own body. In addition, visual targets elicit a motor schema for potential action that maps the position of objects in the surrounding environment, irrespective of whether the corresponding action is actually executed (Jeannerod et al., 1995; Rizzolatti et al., 1997a,b). In their virtual roller coaster scenario, Jäncke et al. (2009) argue that VEs trigger motor schemas mapping the visual objects in terms of real motor space as well as a corresponding plan for potential action.

Another study reports that the activity of the parietal cortex could be also modulated by the object's size (Tarantino et al., 2014), while other authors discuss that parietal areas are involved in integrating information about three-dimensional objects, such as the object size and the grasp-relevant dimension (Monaco et al., 2014). In addition, Salmi et al. (2014) illustrate that the parietal activity related to goal-directed actions could also depend on a behavioral priority accounting for percepts, thoughts and emotions during the observation of natural scenes.

In this regard, the presented results show a theta increase across the right parietal cortex during the perception of pleasant VEs. In agreement with the aforementioned literature, these findings could offer the interpretation that the perceived pleasant VEs may favor the triggering of motor schemas related to potential actions planning.

The perception of pleasant VEs also returned a significant activation of the alpha band in left-central parietal and frontal areas, a fact which might underlie an increase in visuospatial processing. In fact, similar findings were already reported in a study performed with fMRI, which tested the level of pleasantness during the observation of spaces with varying architectural features (ceiling height and openness/enclosure), illustrating the activation of left precuneus and left middle gyrus (Vartanian et al., 2015). These two structures have an important role in visuospatial processing (Kravitz et al., 2011). Other authors argue that this lateralized activation of the left hemisphere could be due to the processing of categorical spatial relations and not to the processing of coordinate spatial relations (Amorapanth et al., 2009). Categorical spatial relations are involved in tasks that do not require a precise location. On the other hand, coordinate spatial relations require precise metrical information about distances among objects (Kosslyn, 1987).

Additional findings report that the left hemisphere is more involved in processing spatial relations, while the activity of the right parietal lobe relates to coordinate spatial relations (Baciu et al., 1999; Suegami and Laeng, 2013). Interestingly, Cela-Conde et al. (2009) show that in women there is a lateralized activity in the left parietal areas during the observation of stimuli rated as beautiful. Asymmetrically, men show an increase of parietal activity in the right hemisphere. Taking an evolutionary perspective, they discuss that women rely more on categorical strategies when processing objects more than men do. Due to the lack of statistical power, evidence supporting this gender differentiation cannot be provided in this study and should be further investigated.

However, since the visual exploration of VEs did not require the processing of specific distance among objects, it is reasonable to think that subjects mostly activated categorical spatial processing during the perception of pleasant environments. This kind of processing could be related to the fact that people were considering the quality of the space as a whole. Vartanian et al. (2015) report a positive linear correlation between the activation of the left precuneus and the scores of pleasantness. Similarly the presented results show a potential role of the left precuneus in the perception of pleasant VEs, an area which also facilitates visuospatial exploration. This finding could be also interpreted according to the biophilic hypothesis (Kellert and Wilson, 1995; McVay et al., 1995), which suggests that the activations of areas for visuospatial exploration could support more general human preferences for appreciating spatial properties that are evolutionary beneficial.

## Embodiment and Affordance

The data indicate a certain degree of similarity in the pattern returned by the mu band pertaining to the perceptual dimensions of Pleasantness and Comfort. In fact, both dimensions highlighted a de-synchronization of such rhythm during the perception of VEs with High Comfort and High Pleasantness scores. Along with several studies showing a primary importance of cognition for art response (Cinzia and Vittorio, 2009; Chatterjee and Vartanian, 2014), recent theories and experimental works propose that the activation of embodied mechanisms play a key role in the aesthetic experience of works of art and that these mechanisms could also account for the perception of architectural spaces (Freedberg and Gallese, 2007; Umilta' et al., 2012; Sbriscia-Fioretti et al., 2013). In summary, the motor system is activated due to an automatic empathic relationship established between the artwork and the observer—a phenomenon which could be triggered by the work's representational content and by artist's creative gestures (Cinzia and Vittorio, 2009). Umilta' et al. (2012) report the suppression of the mu rhythm, recorded around electrodes C3 and C4, during the observation of the cuts on the canvases by Lucio Fontana. Similarly, Sbriscia-Fioretti et al. (2013) illustrate that observing the brushstrokes by Franz Kline engages motor areas along with the occipital circuits related to vision, as well as the frontal and orbitofrontal regions processing reward and judgment, respectively. In both studies, the authors contrasted the EEG activity gathered from the perception of the original works against the activity elicited by the observation of computer-generated reproductions displaying the same patterns of lines and stripes but without the original dynamic components (i.e., artist's gestures). Thus, the described cerebral activations are engendered by the automatic comprehension of those dynamic components and the recognition of the motor actions that produced those works. Moreover, the activity in premotor and motor cortices has been observed in other tasks involving spatial cognition (Rizzolatti and Craighero, 2004). In this study, the perception of VEs rated as pleasant and comfortable could involve spatial cognitive processes, increased somatosensory perception and the planning and execution of movements. In this sense, subjects felt free to "live" those spaces which triggered the embodied mechanism (Freedberg and Gallese, 2007; Cela-Conde et al., 2009).

Similarly, object perception provides an example of embodiment which resides in the action domain. Specifically, the observation of manipulable objects triggers the same motor resources typically employed during the planning and execution of actions targeting the same objects (Gallese and Sinigaglia, 2013). Hence, the motor system can also be engaged in the absence of active action execution. Recent studies show that observing manipulable objects can lead to mu rhythm suppression within 300 ms after stimulus presentation, possibly reflecting the automatic access to object-associated actions (Proverbio, 2012; Rüther et al., 2014). In particular, Proverbio shows that this activation is evident when comparing the observation of manipulable objects (tools) to the observation of non-manipulable objects, mostly in the band between 10 and 12 Hz (Proverbio, 2012). In a similar fashion, Rüther and colleagues report a significant suppression of the mu rhythm when observing familiar tools instead of new ones, although in a band ranging in lower frequencies (i.e., from 8 to 10 Hz; Rüther et al., 2014). Accordingly, during the perception of VEs, the modulation of the mu rhythm seems to depend not only on the simple observation of specific objects in the environment but also on the perception of the environment as a whole. In fact, the analysis regarding Pleasantness essentially compares the VEs with objects against VEs without objects (**Figure 3E**). On the other hand, when analyzing Comfort, the High Comfort condition had both VEs with and without objects, making the comparison with the Low Comfort condition object-balanced (**Figure 3D**). In other words, both the High ($z > 0$) and Low ($z < 0$) Comfort datasets comprise the perception of VEs with and without objects. Therefore, these results show the suppression of the mu rhythm in the conditions of High Pleasantness and High Comfort, which could reflect the possibility to interact with the objects located in the VEs.

Because the objects were perceived in a specific functional configuration instead of being observed independently, this neurophysiological mechanism could have a role in regulating potential actions which influence the pleasantness and comfort of the environment as a whole. These results are in line with other studies performed on object affordances, showing that the functional identity of graspable objects influences the extent to which they are associated with motor representations (Creem-Regehr and Lee, 2005; Proverbio, 2012). Similarly, the object familiarity could enhance the activation of action representations and motor plans (Rüther et al., 2014). Such findings reveal that the view of a tool automatically activates appropriate motoric properties, including its affordance and the representation of the associated motor interaction. In addition, behavioral and brain stimulation studies have also shown that the affordability is context dependent and that spatial constraints affect one's reuse of his/her own action representations (Costantini et al., 2010, 2011; Cardellicchio et al., 2011).

Finally, the analysis of Familiarity and Novelty returned no significant results in the mu band, probably because the EEG activity in both the "high" and "low" groups accounted for the perception of objects with the same function (i.e., affordance) but located in different VEs, and with different design. This can be observed in the distribution of the related behavioral z-scores in **Figures 3B,C**. However, further investigation is needed in order to explore how the perception of affordances depends on the architectural context. This would elucidate the relationship between embodied mechanisms and the specific features of architectural environments.

### Limitations

Due to the explorative nature of the present study, several limitations should be taken into account when considering the final results. First, the tested VEs were designed with the aim to induce different levels of Familiarity, Novelty, Comfort, Pleasantness, and Arousal. Therefore, the corresponding main cerebral activations were investigated regardless of the specific features of the spaces represented (e.g., VE1 vs. VE2). The aim was to test a simple IVR setup and at the same time to effectively retrieve neurophysiological correlates of environment perception. These results could be useful for shaping architectural hypotheses in future studies. Secondly, the electromiographic activity of the subjects enrolled in the data recording was not controlled, still they were asked to seat in the CAVE without moving their legs, arms and hands. During the data collection, the experimenter monitored the behavior of all subjects during the task and did not report any movement of their limbs. Hence, the activity of the motor areas could have been caused only by cerebral processes which are not related with movement execution. Also, the gaze was not controlled using eye-tracking measurements and therefore the objects and locations of the VEs that were the most looked at by the participants could not be defined. Instead, the aim was to retrieve neurophysiological correlates of a generalized perception—that is, of architectural space as a whole and not of the specific visual targets in the environment. Finally, from the architectural point of view, the setup required the participants to explore the VEs with a certain degree of attention. Conversely, in everyday life, people usually do not focus on architectural features but rather live the space in a habitual and automatic manner, without paying special attention to the details of the environment they are experiencing. Due to the correlational design of this work, all the points mentioned above will be addressed with additional control conditions to improve the setup of further experiments.

## CONCLUSIONS

The present findings aim to provide new insights for studying the impact of architecture on human brain. These results revealed that perception of familiar and comfortable real-like VEs engender the activation of those cerebral circuits elicited by the sense of presence which facilitate sensorimotor integration. Similarly, the perception of pleasant environments involves areas devoted to visuospatial processing, suggesting the importance of a fronto-parietal network in aesthetic perception of places. These cerebral areas could be considered as evolutionary beneficial. Finally, a common suppression of the mu rhythm over the left motor areas was reported, characterizing highly pleasant and comfortable environments. These results are in agreement with the embodied simulation theory, which plays a fundamental role in object perception and possibly in the environment perception as a whole. Overall, this study shows the involvement of motor and cognitive processes for the evaluation of architectural environments. Further research is needed for in-depth investigation of the role of embodiment, affordances and perceptual processes underpinning the appreciation of architectural environments. This knowledge will provide neurophysiological findings to improve the design of buildings and help to create environments that satisfy man's demands.

## ACKNOWLEDGMENTS

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## REFERENCES

Aftanas, L. I., and Golocheikine, S. A. (2001). Human anterior and frontal midline theta and lower alpha reflect emotionally positive state and internalized attention: high-resolution EEG investigation of meditation. *Neurosci. Lett.* 310, 57–60. doi: 10.1016/S0304-3940(01)02094-8

Aftanas, L. I., and Golocheikine, S. A. (2002). Non-linear dynamic complexity of the human EEG during meditation. *Neurosci. Lett.* 330, 143–146. doi: 10.1016/S0304-3940(02)00745-0

Aglioti, S. M., and Candidi, M. (2011). Out-of-place bodies, out-of-body selves. *Neuron* 70, 173–175. doi: 10.1016/j.neuron.2011.04.006

Amorapanth, P. X., Widick, P., and Chatterjee, A. (2009). The neural basis for spatial relations. *J. Cogn. Neurosci.* 22, 1739–1753. doi: 10.1162/jocn.2009.21322

Appleton, J. (1996). *The Experience of Landscape*. Revised Edn. Chichester; New York, NY: Wiley.

Baciu, M., Koenig, O., Vernier, M. P., Bedoin, N., Rubin, C., and Segebarth, C. (1999). Categorical and coordinate spatial relations: fMRI evidence for hemispheric specialization. *Neuroreport* 10, 1373–1378. doi: 10.1097/00001756-199904260-00040

Baijal, S., and Srinivasan, N. (2009). Theta activity and meditative states: spectral changes during concentrative meditation. *Cogn. Process.* 11, 31–38. doi: 10.1007/s10339-009-0272-0

Baños, R. M., Botella, C., Rubió, I., Quero, S., García-Palacios, A., and Alcañiz, M. (2008). Presence and emotions in virtual environments: the influence of stereoscopy. *Cyberpsychol. Behav.* 11, 1–8. doi: 10.1089/cpb.2007.9936

Bar, M. (2004). Visual objects in context. *Nat. Rev. Neurosci.* 5, 617–629. doi: 10.1038/nrn1476

Benedek, M., and Kaernbach, C. (2010). A continuous measure of phasic electrodermal activity. *J. Neurosci. Methods* 190, 80–91. doi: 10.1016/j.jneumeth.2010.04.028

Benjamini, Y., and Yekutieli, D. (2001). The control of the false discovery rate in multiple testing under dependency. *Ann. Stat.* 29, 1165–1188. doi: 10.1214/aos/1013699998

Blair, R. C., and Karniski, W. (1993). An alternative method for significance testing of waveform difference potentials. *Psychophysiology* 30, 518–524. doi: 10.1111/j.1469-8986.1993.tb02075.x

Bland, B. H., and Oddie, S. D. (2001). Theta band oscillation and synchrony in the hippocampal formation and associated structures: the case for its role in sensorimotor integration. *Behav. Brain Res.* 127, 119–136. doi: 10.1016/S0166-4328(01)00358-8

Bohil, C. J., Alicea, B., and Biocca, F. A. (2011). Virtual reality in neuroscience research and therapy. *Nat. Rev. Neurosci.* 12, 752–762. doi: 10.1038/nrn3122

Boucsein, W., Fowles, D. C., Grimnes, S., Ben-Shakhar, G., Roth, W. T., Dawson, M. E., et al. (2012). Publication recommendations for electrodermal measurements. *Psychophysiology* 49, 1017–1034. doi: 10.1111/j.1469-8986.2012.01384.x

Bunzeck, N., and Düzel, E. (2006). Absolute coding of stimulus novelty in the human substantia nigra/VTA. *Neuron* 51, 369–379. doi: 10.1016/j.neuron.2006.06.021

Caplan, J. B., Madsen, J. R., Schulze-Bonhage, A., Aschenbrenner-Scheibe, R., Newman, E. L., and Kahana, M. J. (2003). Human theta oscillations related to sensorimotor integration and spatial learning. *J. Neurosci.* 23, 4726–4736.

Cardellicchio, P., Sinigaglia, C., and Costantini, M. (2011). The space of affordances: a TMS study. *Neuropsychologia* 49, 1369–1372. doi: 10.1016/j.neuropsychologia.2011.01.021

Cela-Conde, C. J., Ayala, F. J., Munar, E., Maestú, F., Nadal, M., Capó, M. A., et al. (2009). Sex-related similarities and differences in the neural correlates of beauty. *Proc. Natl. Acad. Sci. U.S.A.* 106, 3847–3852. doi: 10.1073/pnas.0900304106

Cela-Conde, C. J., Marty, G., Maestú, F., Ortiz, T., Munar, E., Fernández, A., et al. (2004). Activation of the prefrontal cortex in the human visual aesthetic perception. *Proc. Natl. Acad. Sci. U.S.A.* 101, 6321–6325. doi: 10.1073/pnas.0401427101

Chatterjee, A., and Vartanian, O. (2014). Neuroaesthetics. *Trends Cogn. Sci.* 18, 370–375. doi: 10.1016/j.tics.2014.03.003

Cinzia, D. D., and Vittorio, G. (2009). Neuroaesthetics: a review. *Curr. Opin. Neurobiol.* 19, 682–687. doi: 10.1016/j.conb.2009.09.001

Costantini, M., Ambrosini, E., Scorolli, C., and Borghi, A. M. (2011). When objects are close to me: affordances in the peripersonal space. *Psychon. Bull. Rev.* 18, 302–308. doi: 10.3758/s13423-011-0054-4

Costantini, M., Ambrosini, E., Tieri, G., Sinigaglia, C., and Committeri, G. (2010). Where does an object trigger an action? An investigation about affordances in space. *Exp. Brain Res.* 207, 95–103. doi: 10.1007/s00221-010-2435-8

Creem-Regehr, S. H., and Lee, J. N. (2005). Neural representations of graspable objects: are tools special? *Brain Res. Cogn. Brain Res.* 22, 457–469. doi: 10.1016/j.cogbrainres.2004.10.006

Cruz-Neira, C., Sandin, D. J., and DeFanti, T. A. (1993). "Surround-screen projection-based virtual reality: the design and implementation of the CAVE," in *Proceedings of the 20th Annual Conference on Computer Graphics and Interactive Techniques SIGGRAPH '93* (New York, NY: ACM), 135–142.

Delorme, A., and Makeig, S. (2004). EEGLAB: an open source toolbox for analysis of single-trial EEG dynamics including independent component analysis. *J. Neurosci. Methods* 134, 9–21. doi: 10.1016/j.jneumeth.2003.10.009

Diemer, J., Alpers, G. W., Peperkorn, H. M., Shiban, Y., and Mühlberger, A. (2015). The impact of perception and presence on emotional reactions: a review of research in virtual reality. *Emot. Sci.* 6:26. doi: 10.3389/fpsyg.2015.00026

Dien, J., and Santuzzi, A. M. (2005). "Application of repeated measures ANOVA to high-density ERP datasets: a review and tutorial," in *Event-Related Potentials: A Methods Handbook*, ed T. Handy (Cambridge, MA: MIT Press), 57–82.

Dietl, T., Dirlich, G., Vogl, L., Lechner, C., and Strian, F. (1999). Orienting response and frontal midline theta activity: a somatosensory spectral perturbation study. *Clin. Neurophysiol.* 110, 1204–1209. doi: 10.1016/S1388-2457(99)00057-7

Dombeck, D. A., and Reiser, M. B. (2012). Real neuroscience in virtual worlds. *Curr. Opin. Neurobiol.* 22, 3–10. doi: 10.1016/j.conb.2011.10.015

Doppelmayr, M., Klimesch, W., Pachinger, T., and Ripper, B. (1998). Individual differences in brain dynamics: important implications for the calculation of event-related band power. *Biol. Cybern.* 79, 49–57. doi: 10.1007/s004220050457

Ekstrom, A. D., Caplan, J. B., Ho, E., Shattuck, K., Fried, I., and Kahana, M. J. (2005). Human hippocampal theta activity during virtual navigation. *Hippocampus* 15, 881–889. doi: 10.1002/hipo.20109

Elbert, T., Ray, W. J., Kowalik, Z. J., Skinner, J. E., Graf, K. E., and Birbaumer, N. (1994). Chaos and physiology: deterministic chaos in excitable cell assemblies. *Physiol. Rev.* 74, 1–47.

Epstein, R., and Kanwisher, N. (1998). A cortical representation of the local visual environment. *Nature* 392, 598–601. doi: 10.1038/33402

Freedberg, D., and Gallese, V. (2007). Motion, emotion and empathy in esthetic experience. *Trends Cogn. Sci.* 11, 197–203. doi: 10.1016/j.tics.2007.02.003

Gallese, V., and Sinigaglia, C. (2013). "Cognition in action: a new look at the cortical motor system," in *Joint Attention and Agency*, eds J. Metcalfe and H. S. Terrace (New York, NY: Oxford University Press), 178–195.

Graham, L. T., Gosling, S. D., and Travis, C. K. (2015). The psychology of home environments: a call for research on residential space. *Perspect. Psychol. Sci. J. Assoc. Psychol. Sci.* 10, 346–356. doi: 10.1177/1745691615576761

Groppe, D. M., Urbach, T. P., and Kutas, M. (2011). Mass univariate analysis of event-related brain potentials/fields I: a critical tutorial review. *Psychophysiology* 48, 1711–1725. doi: 10.1111/j.1469-8986.2011.01273.x

Hyvärinen, A., and Oja, E. (2000). Independent component analysis: algorithms and applications. *Neural Netw.* 13, 411–430. doi: 10.1016/S0893-6080(00)00026-5

Ionta, S., Heydrich, L., Lenggenhager, B., Mouthon, M., Fornari, E., Chapuis, D., et al. (2011). Multisensory mechanisms in temporo-parietal cortex support self-location and first-person perspective. *Neuron* 70, 363–374. doi: 10.1016/j.neuron.2011.03.009

Ishizu, T., and Zeki, S. (2011). Toward a brain-based theory of beauty. *PLoS ONE* 6:e21852. doi: 10.1371/journal.pone.0021852

Jäncke, L., Cheetham, M., and Baumgartner, T. (2009). Virtual reality and the role of the prefrontal cortex in adults and children. *Front. Neurosci.* 3, 52–59. doi: 10.3389/neuro.01.006.2009

Jeannerod, M., Arbib, M. A., Rizzolatti, G., and Sakata, H. (1995). Grasping objects: the cortical mechanisms of visuomotor transformation. *Trends Neurosci.* 18, 314–320. doi: 10.1016/0166-2236(95)93921-J

Kawabata, H., and Zeki, S. (2004). Neural correlates of beauty. *J. Neurophysiol.* 91, 1699–1705. doi: 10.1152/jn.00696.2003

Kellert, S. R., and Wilson, E. O. (1995). *The Biophilia Hypothesis*. Washington, DC: Island Press.

Klimesch, W. (1999). EEG alpha and theta oscillations reflect cognitive and memory performance: a review and analysis. *Brain Res. Brain Res. Rev.* 29, 169–195. doi: 10.1016/S0165-0173(98)00056-3

Kober, S. E., and Neuper, C. (2011). Sex differences in human EEG theta oscillations during spatial navigation in virtual reality. *Int. J. Psychophysiol. Off. J. Int. Organ. Psychophysiol.* 79, 347–355. doi: 10.1016/j.ijpsycho.2010.12.002

Kosslyn, S. M. (1987). Seeing and imagining in the cerebral hemispheres: a computational approach. *Psychol. Rev.* 94, 148–175. doi: 10.1037/0033-295X.94.2.148

Kravitz, D. J., Saleem, K. S., Baker, C. I., and Mishkin, M. (2011). A new neural framework for visuospatial processing. *Nat. Rev. Neurosci.* 12, 217–230. doi: 10.1038/nrn3008

Kubota, Y., Sato, W., Toichi, M., Murai, T., Okada, T., Hayashi, A., et al. (2001). Frontal midline theta rhythm is correlated with cardiac autonomic activities during the performance of an attention demanding meditation procedure. *Cogn. Brain Res.* 11, 281–287. doi: 10.1016/S0926-6410(00)00086-0

Kühn, S., and Gallinat, J. (2012). The neural correlates of subjective pleasantness. *Neuroimage* 61, 289–294. doi: 10.1016/j.neuroimage.2012.02.065

Lindal, P. J., and Hartig, T. (2013). Architectural variation, building height, and the restorative quality of urban residential streetscapes. *J. Environ. Psychol.* 33, 26–36. doi: 10.1016/j.jenvp.2012.09.003

Lorteije, J. A., Kenemans, J. L., Jellema, T., van der Lubbe, R. H., de Heer, F., and van Wezel, R. J. A. (2006). Delayed response to animate implied motion in human motion processing areas. *J. Cogn. Neurosci.* 18, 158–168. doi: 10.1162/jocn.2006.18.2.158

Mallgrave, H. F., and Ikonomou, E. (1994). *Empathy, Form, and Space: Problems in German Aesthetics, 1873-1893*. Santa Monica, CA: Getty Publications Programs.

McVay, S., Katcher, A., McCarthy, C., Wilkins, G., Ulrich, R., Shepard, P., et al. (1995). *The Biophilia Hypothesis*. Reissue Edn. Edited by S. R. Kellert and E. O. Wilson. Washington, DC: Island Press.

Meehan, M., Razzaque, S., Insko, B., Whitton, M., and Brooks, F. P. (2005). Review of four studies on the use of physiological reaction as a measure of presence in stressful virtual environments. *Appl. Psychophysiol. Biofeedback* 30, 239–258. doi: 10.1007/s10484-005-6381-3

Mitchell, D. J., McNaughton, N., Flanagan, D., and Kirk, I. J. (2008). Frontal-midline theta from the perspective of hippocampal "theta." *Prog. Neurobiol.* 86, 156–185. doi: 10.1016/j.pneurobio.2008.09.005

Monaco, S., Chen, Y., Medendorp, W. P., Crawford, J. D., Fiehler, K., and Henriques, D. Y. (2014). Functional magnetic resonance imaging adaptation reveals the cortical networks for processing grasp-relevant object properties. *Cereb. Cortex* 24, 1540–1554. doi: 10.1093/cercor/bht006

Pan, J., and Tompkins, W. J. (1985). A real-time QRS detection algorithm. *IEEE Trans. Biomed. Eng.* 32, 230–236. doi: 10.1109/TBME.1985.325532

Parsons, T. D., and Rizzo, A. A. (2008). Affective outcomes of virtual reality exposure therapy for anxiety and specific phobias: a meta-analysis. *J. Behav. Ther. Exp. Psychiatry* 39, 250–261. doi: 10.1016/j.jbtep.2007.07.007

Plancher, G., Barra, J., Orriols, E., and Piolino, P. (2013). The influence of action on episodic memory: a virtual reality study. *Q. J. Exp. Psychol.* 66, 895–909. doi: 10.1080/17470218.2012.722657

Proverbio, A. M. (2012). Tool perception suppresses 10-12Hz μ rhythm of EEG over the somatosensory area. *Biol. Psychol.* 91, 1–7. doi: 10.1016/j.biopsycho.2012.04.003

Rizzolatti, G., and Craighero, L. (2004). The mirror-neuron system. *Annu. Rev. Neurosci.* 27, 169–192. doi: 10.1146/annurev.neuro.27.070203.144230

Rizzolatti, G., Fadiga, L., Fogassi, L., and Gallese, V. (1997a). The space around Us. *Science* 277, 190–191. doi: 10.1126/science.277.5323.190

Rizzolatti, G., Fogassi, L., and Gallese, V. (1997b). Parietal cortex: from sight to action. *Curr. Opin. Neurobiol.* 7, 562–567. doi: 10.1016/S0959-4388(97)80037-2

Rüther, N. N., Brown, E. C., Klepp, A., and Bellebaum, C. (2014). Observed manipulation of novel tools leads to mu rhythm suppression over sensory-motor cortices. *Behav. Brain Res.* 261, 328–335. doi: 10.1016/j.bbr.2013.12.033

Salmi, J., Glerean, E., Jääskeläinen, I. P., Lahnakoski, J. M., Kettunen, J., Lampinen, J., et al. (2014). Posterior parietal cortex activity reflects the significance of others' actions during natural viewing. *Hum. Brain Mapp.* 35, 4767–4776. doi: 10.1002/hbm.22510

Sammler, D., Grigutsch, M., Fritz, T., and Koelsch, S. (2007). Music and emotion: electrophysiological correlates of the processing of pleasant and unpleasant music. *Psychophysiology* 44, 293–304. doi: 10.1111/j.1469-8986.2007.00497.x

Sanchez-Vives, M. V., and Slater, M. (2005). From presence to consciousness through virtual reality. *Nat. Rev. Neurosci.* 6, 332–339. doi: 10.1038/nrn1651

Sato, N., and Nakamura, K. (2003). Visual response properties of neurons in the parahippocampal cortex of monkeys. *J. Neurophysiol.* 90, 876–886. doi: 10.1152/jn.01089.2002

Sbriscia-Fioretti, B., Berchio, C., Freedberg, D., Gallese, V., and Umiltà, M. A. (2013). ERP modulation during observation of abstract paintings by Franz Kline. *PLoS ONE* 8:e75241. doi: 10.1371/journal.pone.0075241

Schomaker, J., van Bronkhorst, M. L., and Meeter, M. (2014). Exploring a novel environment improves motivation and promotes recall of words. *Front. Psychol.* 5:918. doi: 10.3389/fpsyg.2014.00918

Senkowski, D., Saint-Amour, D., Kelly, S. P., and Foxe, J. J. (2007). Multisensory processing of naturalistic objects in motion: a high-density electrical mapping and source estimation study. *Neuroimage* 36, 877–888. doi: 10.1016/j.neuroimage.2007.01.053

Slater, M. (1999). Measuring presence: a response to the witmer and singer presence questionnaire. *Presence* 8, 560–565. doi: 10.1162/105474699566477

Slater, M., Spanlang, B., and Corominas, D. (2010). "Simulating virtual environments within virtual environments as the basis for a psychophysics of presence," in *ACM SIGGRAPH 2010 Papers* SIGGRAPH '10, Vol. 92 (New York, NY: ACM), 1–92.

Slater, M., and Wilbur, S. (1997). A Framework for Immersive Virtual Environments (FIVE) - speculations on the role of presence in virtual environments. *Presence* 6, 603–616. doi: 10.1162/pres.1997.6.6.603

Slobounov, S. M., Ray, W., Johnson, B., Slobounov, E., and Newell, K. M. (2015). Modulation of cortical activity in 2D versus 3D virtual reality environments: an EEG study. *Int. J. Psychophysiol.* 95, 254–260. doi: 10.1016/j.ijpsycho.2014.11.003

Stam, C. J. (2003). Chaos, continuous EEG, and cognitive mechanisms: a future for clinical neurophysiology. *Am. J. Electroneurodiagnostic Technol.* 43, 211–227. doi: 10.1080/1086508X.2003.11079444

Stam, C. J. (2005). Nonlinear dynamical analysis of EEG and MEG: review of an emerging field. *Clin. Neurophysiol.* 116, 2266–2301. doi: 10.1016/j.clinph.2005.06.011

Stam, C. J. (2006). *Nonlinear Brain Dynamics*. New York, NY: Nova Publishers.

Stam, C. J., and de Bruin, E. A. (2004). Scale-free dynamics of global functional connectivity in the human brain. *Hum. Brain Mapp.* 22, 97–109. doi: 10.1002/hbm.20016

Stamps, A. E. (1999). Physical determinants of preferences for residential facades. *Environ. Behav.* 31, 723–751. doi: 10.1177/00139169921972326

Suegami, T., and Laeng, B. (2013). A left cerebral hemisphere's superiority in processing spatial-categorical information in a non-verbal semantic format. *Brain Cogn.* 81, 294–302. doi: 10.1016/j.bandc.2012.10.012

Tankus, A., and Fried, I. (2012). Visuomotor coordination and motor representation by human temporal lobe neurons. *J. Cogn. Neurosci.* 24, 600–610. doi: 10.1162/jocn_a_00160

Tarantino, V., De Sanctis, T., Straulino, E., Begliomini, C., and Castiello, U. (2014). Object size modulates fronto-parietal activity during reaching movements. *Eur. J. Neurosci.* 39, 1528–1537. doi: 10.1111/ejn.12512

Tarr, M. J., and Warren, W. H. (2002). Virtual reality in behavioral neuroscience and beyond. *Nat. Neurosci.* 5(Suppl.), 1089–1092. doi: 10.1038/nn948

Tecchia, F., Carrozzino, M., Bacinelli, S., Rossi, F., Vercelli, D., Marino, G., et al. (2010). A flexible framework for wide−spectrum VR development. *Presence* 19, 302–312. doi: 10.1162/PRES_a_00002

Thakral, P. P., Moo, L. R., and Slotnick, S. D. (2012). A neural mechanism for aesthetic experience. *Neuroreport* 23, 310–313. doi: 10.1097/WNR.0b013e328351759f

Tieri, G., Tidoni, E., Pavone, E. F., and Aglioti, S. M. (2015a). Mere observation of body discontinuity affects perceived ownership and vicarious agency over a virtual hand. *Exp. Brain Res.* 233, 1247–1259. doi: 10.1007/s00221-015-4202-3

Tieri, G., Tidoni, E., Pavone, E. F., and Aglioti, S. M. (2015b). Body visual discontinuity affects feeling of ownership and skin conductance responses. *Sci. Rep.* 5, 17139. doi: 10.1038/srep17139

Tirsch, W. S., Stude, P., Scherb, H., and Keidel, M. (2004). Temporal order of nonlinear dynamics in human brain. *Brain Res. Brain Res. Rev.* 45, 79–95. doi: 10.1016/j.brainresrev.2004.01.002

Umilta', M. A., Berchio, C., Sestito, M., Freedberg, D., and Gallese, V. (2012). Abstract art and cortical motor activation: an EEG study. *Front. Hum. Neurosci.* 6:311. doi: 10.3389/fnhum.2012.00311

Urgesi, C., Aglioti, S. M., Skrap, M., and Fabbro, F. (2010). The spiritual brain: selective cortical lesions modulate human self-transcendence. *Neuron* 65, 309–319. doi: 10.1016/j.neuron.2010.01.026

Vanni, S., Revonsuo, A., and Hari, R. (1997). Modulation of the parieto-occipital alpha rhythm during object detection. *J. Neurosci.* 17, 7141–7147.

Vartanian, O., and Goel, V. (2004). Neuroanatomical correlates of aesthetic preference for paintings. *Neuroreport* 15, 893–897. doi: 10.1097/00001756-200404090-00032

Vartanian, O., Navarrete, G., Chatterjee, A., Fich, L. B., Gonzalez-Mora, J. L., Leder, H., et al. (2015). Architectural design and the brain: effects of ceiling height and perceived enclosure on beauty judgments and approach-avoidance decisions. *J. Environ. Psychol.* 41, 10–18. doi: 10.1016/j.jenvp.2014.11.006

Vartanian, O., Navarrete, G., Chatterjee, A., Fich, L. B., Leder, H., Modroño, C., et al. (2013). Impact of contour on aesthetic judgments and approach-avoidance decisions in architecture. *Proc. Natl. Acad. Sci. U.S.A.* 110, 10446–10453. doi: 10.1073/pnas.1301227110

Vecchiato, G., Astolfi, L., De Vico Fallani, F., Cincotti, F., Mattia, D., Salinari, S., et al. (2010a). Changes in brain activity during the observation of TV commercials by using EEG, GSR and HR measurements. *Brain Topogr.* 23, 165–179. doi: 10.1007/s10548-009-0127-0

Vecchiato, G., De Vico Fallani, F., Astolfi, L., Toppi, J., Cincotti, F., Mattia, D., et al. (2010b). The issue of multiple univariate comparisons in the context of neuroelectric brain mapping: an application in a neuromarketing experiment. *J. Neurosci. Methods* 191, 283–289. doi: 10.1016/j.jneumeth.2010.07.009

Vecchiato, G., Toppi, J., Astolfi, L., De Vico Fallani, F., Cincotti, F., Mattia, D., et al. (2011a). Spectral EEG frontal asymmetries correlate with the experienced pleasantness of TV commercial advertisements. *Med. Biol. Eng. Comput.* 49, 579–583. doi: 10.1007/s11517-011-0747-x

Vecchiato, G., Toppi, J., Astolfi, L., Mattia, D., Malerba, P., Scorpecci, A., et al. (2011b). Investigation on the pleasantness of music perception in monolateral and bilateral cochlear implant users by using neuroelectrical source imaging: a pilot study. *Conf. Proc. IEEE Eng. Eng. Med. Biol. Soc.* 2011, 8110–8113. doi: 10.1109/iembs.2011.6092000

Welch, P. D. (1967). The use of fast Fourier transform for the estimation of power spectra: a method based on time averaging over short, modified periodograms. *IEEE Trans. Audio Electroacoustics* 15, 70–73. doi: 10.1109/TAU.1967.1161901

Witmer, B. G., and Singer, M. J. (1998). Measuring presence in virtual environments: a presence questionnaire. *Presence* 7, 225–240. doi: 10.1162/105474698565686

Yue, X., Vessel, E. A., and Biederman, I. (2007). The neural basis of scene preferences. *Neuroreport* 18, 525–529. doi: 10.1097/WNR.0b013e328091c1f9

Zeki, S. (1999). *Inner Vision: An Exploration of Art and the Brain.* Oxford: Oxford University Press.

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