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A critical review on the impact of built environment on users' measured brain activity

Sameh Azzazy [a], Amirhosein Ghaffarianhoseini [a], Ali GhaffarianHoseini [a], Nicola Naismith [a] and Zohreh Doborjeh [b]*

[a]Built Environment Engineering Department, Auckland University of Technology (AUT), Auckland, New Zealand; [b]Knowledge Engineering and Discovery Research Institute (KEDRI), Auckland University of Technology (AUT), Auckland, New Zealand

ABSTRACT
Due to the ever-increasing demand for urbanized life and fast-constructed built environments, the urban quality of life and the psychological wellbeing of the inhabitants are often neglected. This has led to the current built environment that we spend most of our lives in, without adequate investigation into how it impacts the human mental health and well-being. This paper aims to review and analyse the research efforts that investigate 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. The reviewed literature establishes that while in a natural environment, the brain activities are more disentangled and meditative. While in a built environment, the human brain has shown higher levels of stress. However, the mechanism in which the built environment impacts the brain is not yet thoroughly investigated. In this paper, we have identified the current gaps to help shape the future towards a restorative built environment with knowledge about the human mind to maximize user benefits and wellbeing. In conclusion, there was only one design element, using curvatures in interior design, that was identified as more encouraging for higher engaging brain activity that reflects the attraction of the brain to the surroundings. However, in the current neuro-architecture related research, there are still various areas highlighted in this paper that require further intensive research into different scales; interior, building and, urban design, to guide future regulations towards a healthier built environment.

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KEYWORDS
Neuro-architecture; built environment; wellbeing; urban health; urban perceptionâĂŇ; environmental psychology

1. Introduction

Due to the increasing urban growth, by 2050 more than two billion people will be accommodated in new buildings added to the current urban landscape. By 2030, the urban developed land is expected to increase by more than one million km^2 (Goldhagen 2017; Seto et al. 2011). This ever-growing need for building human habitats has impacted the environment, either by the land utilization for buildings or material exploration, and/or emissions (Häfliger et al. 2017). Recently, the built environment industry is aiming to reduce its footprint on the environment. Using smart technologies and building management systems, the built environment became more efficient and can save up to 20–40% of energy consumed in the building which leads to less impact on the environment (D'Oca, Hong, and Langevin 2018; Dounis and Caraiscos 2009).

The increasing scientific interest in greener buildings, as shown in Figure 1, has led to establishing a growing number of green building ratings, such as LEED, BREEAM and Green Star NZ (Doan et al. 2017; Shan and Hwang 2018). Likewise, there has been growing scientific research interest in recent years towards physical well-being and the concept of a healthy built environment (Bluyssen 2010; Ellard 2015; Ghaffarianhoseini et al. 2018; Sarkar and Webster 2017). These Green Buildings ratings may have contributed to guide the scientific interest towards achieving a healthier built environment and considering similar ratings for wellbeing. For instance, using biophilic approaches could shift the green building practice towards human health and well-being (Illankoon et al. 2017; Xue et al. 2019). However, the impact of the built environment on our psychological well-being is not sufficiently investigated. As shown in Figure 1, there is a significant gap between the increasing scientific interest in green building ratings and the impact of the built environment on the human brain, even though they both are following similar trend.

Since the nineteenth century, scientists have sought to understand the formidable complexities of the highly-interconnected system that underpins human thought, emotion and behaviour (Abdullah et al. 2015; Alarcão and Fonseca 2019; Bullmore and Sporns 2009). The human brain is comprised of billions of interconnected cells known as neurons. These fundamental processing elements exchange information biochemically and via electrical pulses that create a spatiotemporal trajectory of sequential activities (Telesford et al. 2011) that culminates in human psychological reactions under different situations. The neural receptors, which functionally and practically covers all the scenes, are connected to the central nervous system – the brain and spinal cord – which control the human life (Gottfried 2011; Papale et al. 2016). The central nervous system collects information from the entire body and coordinates activity across the whole organism to govern all forms of activities from the heart

CONTACT Sameh Azzazy sameh.azzazy@aut.ac.nz
*Present address: Center for Brain Research, Faculty of Medical and Health Sciences, The University of Auckland
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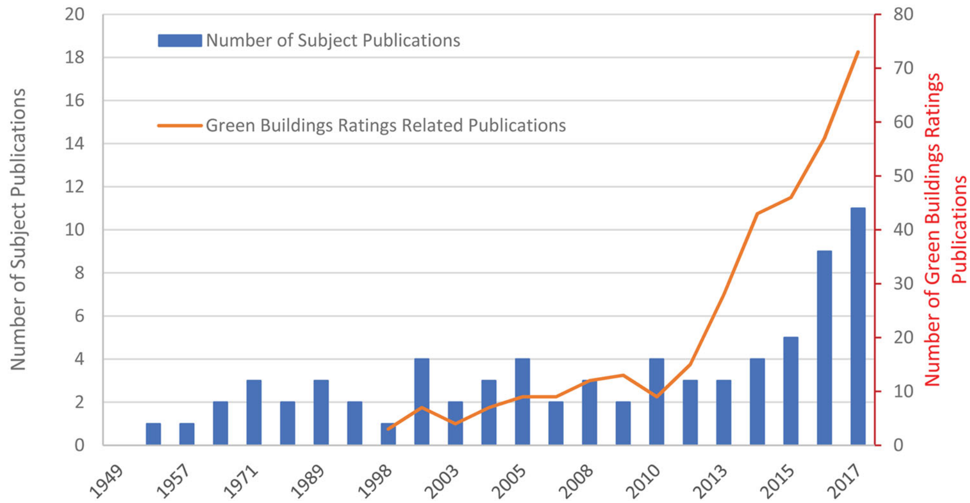

Figure 1. Subject-related publication against green buildings ratings related publications, showing the significant increase in green buildings related publication over a shorter period.

beat and involuntary reflexes, to deep thoughts and creative ideas, hence it forms our perceptual memory which encompass our mental wellbeing (Bermudez-Rattoni 2007; Kandel and Mack 2013; Milner and Rugg 2013).

Even though the contemporary scientific definition of psychological well-being is broad and considers different aspects in Hedonic and Eudaimonic, and even physical features (Ryan and Deci 2001; Ryff, Singer, and Dienberg Love 2004; Sheldon, Corcoran, and Prentice 2018), this research is focused on the momentary experience of the built environment as it manifests in the human neural system; more precisely the brain. This impact of the built environment on the brain functions can be measured and analysed by suitable brain mapping technology (Kluetsch et al. 2014; Urry et al. 2004). Although it is a temporary insight, it will reflect on the user's long-term psychological well-being (Schoenberg et al. 2018), as positive brain activity signifies physical and mental health (Bonnes and Secchiaroli 1995; Diener and Chan 2011). The result of the brain mapping recordings could indicate the user's state of mind, which is a measurement of his/her mood and can indicate the level of Engagement, Interest, Disengagement, Creative Inspiration, Attention, Cognition, Focus, etc. (Gegenfurtner et al. 2017; Misulis 2013; Nidal and Malik 2014; Schoenberg et al. 2018).

In the literature, few studies used scientific instrument measurements such as brain scanning, instead of the more common psychological analysis to investigate the impact of the built environment on the mental health. This lack of adequate research is incongruous to the impact of the subject, since the average time spent inside the built environment is 90% of the average lifespan (Evans and McCoy 1998; Hillier and Hanson 1989). This portion of our life span forms an essential relationship between our inner self and the surroundings that justify our behaviour (Ellard 2015; Proulx et al. 2016).

This paper aims to review several related research efforts that investigate the impact of built environments on the human state of mind, and the different methodologies/technologies used to measure that impact. It predominantly focuses on the impacts on users' momentary brain activities and their neural systems. To better understand the interrelationship between the human brain and the built environment, in context of this paper, the following terminologies should be identified:

The Built Environment	All levels (urban, building, interior, etc.) of the manmade structures that we interact with using our senses (i.e. sight, hearing, smell, taste and touch)(Arbib 2015b).
Stimulus	Any element (colour, sound, design, etc.) of the built environment that evokes or sparks a corresponding nerve or neuron receptor in the human body (Bear, Connors, and Paradiso 2016).
Momentary Experience	The transitory integration of all the stimuli which is processed by the human brain to form a temporary state of mind (Minsky 2007).
State of Mind	The mood or mental state at a certain time which justifies the human momentary behaviour and feelings, e.g. Engagement, Disappointment, Unwind, Cognition, Focus, etc. Recently, these indications can be measured using brain mapping technologies (Schoenberg et al. 2018; Varela et al. 2017)
Functional Brain Mapping	Advanced techniques dependent on sophisticated instruments to scan the brain waves (actual neuron sparks) with high time resolution, faster response, and the ability to plot the brain activities in real time to indicate the state of mind (Bear, Connors, and Paradiso 2016), such as Functional Magnetic Resonance Imaging MRI (fMRI) and Electro-Encephalography (EEG).
Electro-Encephalography (EEG)	EEG is considered the most common instrument for functional mapping and real-time brain wave scanning. It records and amplifies the brain's electrical signals over time to identify the corresponding indication of the subject's state of mind, by the measurement of five main waves (Cruz-Garza et al. 2017; Radüntz 2018).

2. Method

This study conducts a comprehensive literature review of the relationship between the built environment and the human state of mind. It aims to identify the impact of the built environment on the human brain and critically analyse the available literature to guide the future research for healthier built environment that enhance the user experience.

In this regard, using systematic literature review following preferred reporting items for systematic reviews (Moher et al. 2009), a comprehensive literature search based on 'title/abstract/keyword' was conducted. The keywords used in the literature search were generally wide ranging and included terms related to 'built environment, buildings, urban, architecture, mental health, wellbeing, EEG, neuroscience, brain mapping' in the available academic journal databases.

The databases included: Google Scholar; ScienceDirect; Scopus and Springer. Moreover, exploring the list of references of the already found articles, few papers not covered in the above databases, yet considerably important for the review were identified. Using various search engines to explore the literature assured that the weakness of one source can be covered by the strength of another. In addition, a grey literature search was conducted through Google's general search engine, using similar search terms with the aim of identifying relevant unpublished materials, government reports, and policy statements related to the subject.

During this review, over 150 articles were originally identified and classified whilst through employing content analyses, all resources were critically analysed. Only 87 papers were related to the main subject with only 52 original research study papers relating to the built environment, most of which were psychological studies. This trend was also reflected in the publication as in Table 1.

The acquired information concerned with various aspects of the built environment that impact the human brain, were initially recorded in a spreadsheet, separated into columns corresponding to 'Design Elements', 'Built environment scale', 'Research methodologies and technologies', and 'Key Outputs'. The adoption of this research approach enabled the authors to systematically explore the existing body of literature, retrieve the relevant information and highlight the gap of knowledge. During the content analysis, notwithstanding the extensiveness of the collected data and synthetic process of analysing their embedded information related to the objectives of study, few limitations can be highlighted: (1) Published in recognized scientific journals or conference proceedings in the related field, (2) Investigating, in partial or entirety, the built environment, (3) Have a generic scope, i.e. not only considering a specific category such as age or gender or mental illness, as was noticed in many excluded researches, (4) The collected data and the content analysis were limited to the early mentioned utilized search engines, databases and applied research terms.

In this research, it was found that 69% of the publications were in non-engineering or non-built environment related journals. This is considered a significant research shortage since the interference and input of medical professionals on the development process of the built environment is minimal. However, there is a noticed increase in the scientific interest as projected in the publication timeline, as shown in Figure 1.

Although the psychological and social research efforts were acknowledged, the focus of this paper is to identify the measured impact of the built environment on the neural system (the brain) which indicates the state of mind. Hence all the studies depending on scientific instrument measurements, i.e. brain mapping, were mentioned in detail and critically analysed to guide future research.

3. Neuro-architecture

Due to the increasing scientific interest to investigate connections between the built environment and the human neural system, the term 'neuro-architecture' ascended to describe the related research efforts.

3.1. *Definition*

Neuro-architecture unites architecture and neuroscience to better understand the relationship between the human brain and the surrounding built environment. This linking is possible through different scientific techniques such as the observation of responses, physiological measures, psychological analysis and more importantly; functional mapping of different regions of the brain (Eberhard 2009; Goldhagen 2017). Embracing this interdisciplinary study will help to propel us into the future of architecture and design, where human health and happiness are placed at the fore. With this ever-expanding understanding of how and why humans react to environmental stimuli in built spaces, findings in neuro-architecture will increasingly inform design strategies and decisions.
According to Dougherty and Arbib (2013)

> Neuro-architectural studies architecture in terms of the effect of the built environment on the human brain: 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.

In another definition, neuro-architecture analyses the relationship between sensory experience within the built environment, as an input, and our perception of architectural spaces as an output (Papale et al. 2016). The momentary experience, as defined earlier in section 1, can be accurately indicated by brain mapping. After analysis, it can indicate the state of mind of the user which is a measurement of the user mood and can specify the level of engagement, attention, cognition, focus, etc. This measurement of the impact on the human state of mind, even being temporary, will indicate how the built environment performing its function and will reflect on the long term of the psychological well-being of users (Schoenberg et al. 2018).

In general, the main objective of neuro-architecture is to study the impact of the built environment on the neural system; which is the manifestation of human perception and an indicator of psychological well-being (Bluyssen 2010; Pykett 2015). These clear attempts have been developing throughout history, using the available research tools, of their time, to understand how the brain perceives its surroundings (Ellard 2015; Jelić et al. 2016). Only in recent decades the advances in medical instruments, particularly radiology and brain mapping, allowed researchers to

Table 1. Number of related publications, based on original study, in each academic journal.

Journal		Number of related papers	Total
Built environment related	Building and Environment	4	16
	Landscape and Urban Planning	3	
	Intelligent Buildings International	3	
	Urban Forestry & Urban Greening	2	
	Architectural Science Review	2	
	Frontiers of Architectural Research	2	
Medical/Psychology related	Journal of Environmental Psychology	7	36
	Cell (and related sub-journals)	5	
	Frontiers in Psychology	4	
	Environment and Behaviour	3	
	Procedia – Social and Behavioural Sciences	3	
	Frontiers in Human Neuroscience	2	
	International Journal of Parallel, Emergent and Distributed Systems	2	
	Journal of Cognitive Neuroscience	2	
	Journal of Transport & Health	2	
	Investigative Ophthalmology & Visual Science	2	
	Brain and Language	1	
	Journal of Cognitive Neuroscience	1	
	British Journal of Sports Medicine	1	
	Health Place	1	

study the impact on the neural system (Nanda et al. 2013; Papale et al. 2016).

3.2. Background

Historically, and long before the forming of neuro-architecture, there have been ancient attempts to relate the built environment to health, such as ‘Sthapatya Veda’ or ‘Maharishi Vedic architecture’ (Bonshek 2001; Jakupi 2016). These are general architectural design principles depending mainly on the orientation and layout of the house; aiming for human health and better connection between the inhabitant and habitat (Fergusson, Wells, and Kettle 2017; Travis et al. 2005).

The early scientific studies, as viewed in the literature, are mainly related to environmental psychology. In the late 1950s architects and behavioural scientists started to work together to design buildings with a specific purpose such as Osmond (1957); where he presented the cooperation between psychiatrists and architects for a specially designed functional building (a psychiatric hospital).

One of the pioneers to focus their research on the relationship between human psychology and the surrounding built environment was Roger G. Barker, particularly on the impact of school environments on children’s psychological health. He was also the first to investigate the environment and behaviour differences between two different cities (Barker and Gump 1964; Barker and Wright 1954).

Since the 1960s there has been a growing interest from researchers, mostly from a social and psychological background, which has led to the publication of two journals: ‘Environment and Behaviour’ in 1969 and ‘Environmental Psychology’ in 1980. Following that was the formation of the first professional research association; The International Association of People-Environment Studies, which was established in 1981 (Bell 2001).

The term ‘Neuroscience’ was first mentioned regarding building design in an interview from the 2003 fall issue of Society for Neuroscience, where Eberhard and Gage explained why architects and neuroscientists are beginning to work together. The same issue included the announcement of the formation of the first academic research body that focuses on neuro-architecture (the Academy of Neuroscience for Architecture (ANFA)) (Arellano 2015; Eberhard and Gage 2003). ANFA was formed in San Diego in 2003 and is considered the first research institute to sponsor and develop the utilization of neuroscience research to better understand the human interaction with the built environment (ANFA 2003).

This evolution of research interests, as shown in Figure 2, has led to various studies with different research methodologies to investigate the impact of the surrounding environment on the human brain. In general, the research approaches can be categorized in two main types of studies; Psychological Analysis and Brain Mapping.

4. Research approaches

The study of the human brain has been developing from ancient philosophical ideas to sophisticated and complex medical instruments. Similarly, the research studies found in the literature have developed from psychological analyses to technological analyses, depending on instrumental measurements. Most of the reviewed studies investigated the impact of the surrounding environment on the human experience. The higher percentage are using social and psychological analyses, as shown in Figure 3.

Arguably both have advantages, psychological analysis studies are more indicative for long-term psychological well-being, whereas brain mapping depends on accurate and advanced scientific measurement but is more momentary in nature (Emmons and King 1988; Urry et al. 2004). Therefore, to isolate the impact of only the built environment on the long-term psychological well-being, the momentary measurement is considered more indicative (Arbib 2015a).

Due to the technological limitation, the brain mapping studies have a much lower scale compared to the psychological studies. Only in recent decades, the emergence of scientific technologies has allowed researchers to accurately detect the brain activity that indicates different states of mind (Arbib 2012; Nanda et al. 2013). On the other hand, the reviewed psychological

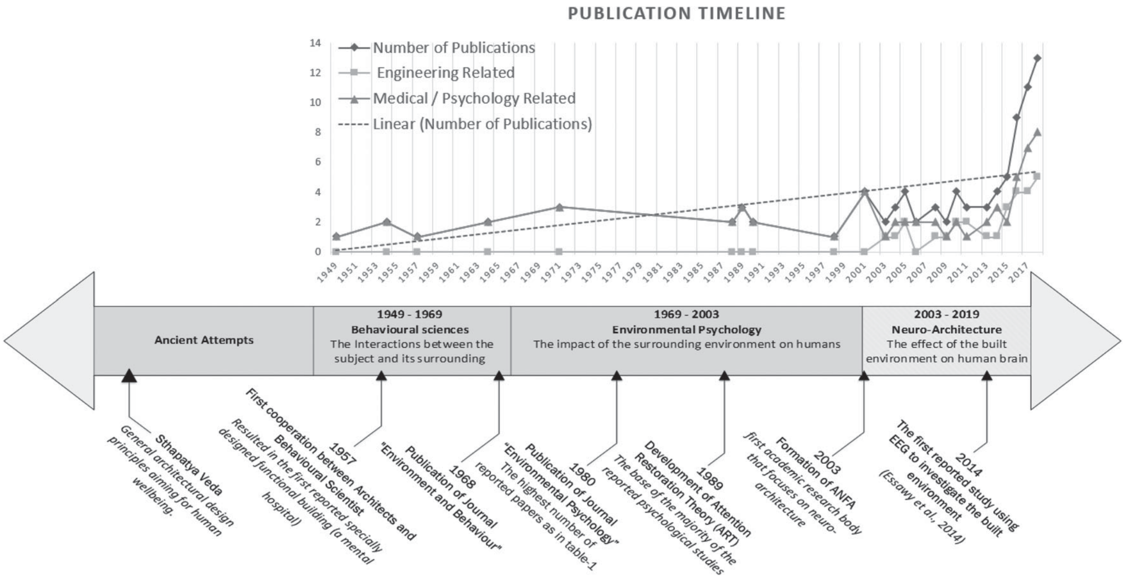

Figure 2. Subject timeline with related milestones, showing the development of scientific interest from Behavioural Science to Neuro-Architecture along with related publication timeline.

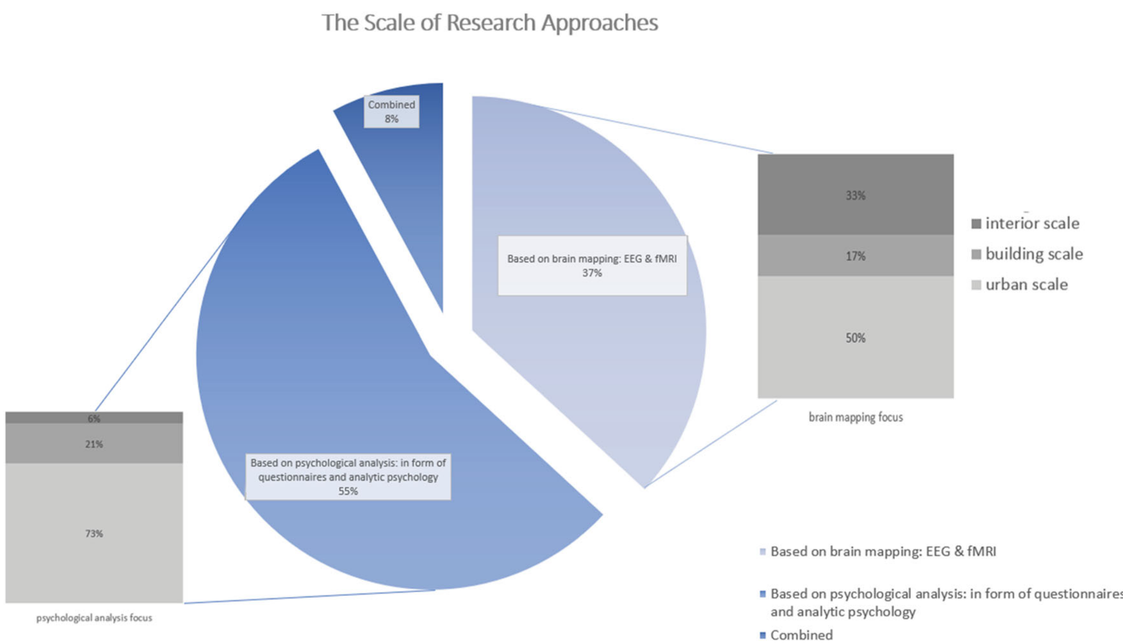

Figure 3. The scales of the different research approaches demonstrated in the literature, these numbers are only for experiment or scientific measurement-based research. The percentage is based on a total of 52 reported studies.

analysis studies are not strongly dependent on technology and scientific instruments.

4.1. Psychological approach

Psychological studies can be based on self-reported questionnaires, an investigative interview conducted by a specialist, or such other analytical techniques, to report the subject's state of mind. They are mainly designed to measure the mood or mental state of the subject, e.g. Brunel Mood Scale also known as BRUMS, Profile of Moods States (POMS), Positive and Negative Affect Schedule (PANAS) which is a self-reported scale-based questionnaire, and Backward Digit Span (BDS) which is a measure of working memory used to assess the brain functions (Berman, Jonides, and Kaplan 2008; McNair and Heuchert 2007; Watson, Clark, and Tellegen 1988).

Most of the studies are related to the Attention Restoration Theory (ART) which proved, and explained, that exposure to nature leads to positive effects on psychological health. According to ART, most natural scenes capture the attention in an enjoyable and straightforward manner, letting the brain to rest and wander freely (Kaplan and Kaplan 1989).

4.2. Psychological studies in the literature

In their work, Van den Berg, Joye, and Koole (2016) have investigated the difference between viewing nature and the built environment. They used different scaled photos that showed different levels of complicity in both nature and the built environment. By measuring the time of viewing and the subject feedback, they concluded that the participants had positive responses to natural scenes and to the fractal patterns that are more commonly found in nature. Fractal patterns and complexity, when applied to nature, can differentiate the order and structure of repeated-simple patterns that form complex scenes in natural environments, by the repetition of similar visual information across multiple scale levels. This is established by the fact that natural scenes retain roughly the same number of elements and form as one zooms in and out of the scene. The development of fractal geometry was strongly linked the mathematical description of forms and shapes that are found in nature such as mountain ranges and coastlines (Mandelbrot 1982). This suggests that fractal complexity may be a key factor that makes natural scenes more attractive and uplifting than man made building scenes. Therefore, fractal dimension for natural landscape preference can produce designing guidance to imitate nature in the built environment (Hagerhall, Purcell, and Taylor 2004). Depending on the same theory of ART, Valtchanov and Ellard (2015) conducted a similar study, using images with different resolution. Their research confirmed that viewing urban scenes increased blink rates and cognitive load compared to displaying scrambled, low resolution images and natural images.

Stigsdotter et al. (2017b) aimed to identify which qualities and perceived sensory dimensions (PSD) of the natural environment have a healing psychological impact. The result showed that PSDs of peaceful, diverse, natural surroundings have the highest psychologically healing results. This study shows the potential for using the PSDs as guiding principles for designing healthier built environments (Grahn and Stigsdotter 2010).

Few studies have used physiological measurement along with psychological measurement for validation. Stigsdotter et al. (2017a) measured systolic and diastolic blood pressure and Heart Rate Variability (HRV) as an indicator for the body's state of tension or relaxation. Similar to this study, Gidlow et al. (2016) used HRV measurements but adding salivary cortisol and Rate of Perceived Exertion (RPE) measurements. Their results proved that walking in a natural environment leads to greater restorative experience and better cognitive function.

There are other, early mentioned, research efforts that have used psychological approaches to identify the impact of the Indoor Environment Quality (IEQ) on the humane experience, such as: Mendell and Heath (2005); Tham and Willem (2010); Tsutsumi et al. (2007); Wargocki et al. (2000). These efforts, even though they show a direct relationship between IEQ and the user's performance, have not established the direct impact on the user's mental state which manifests as performance (Schoenberg et al. 2018).

The literature includes more studies, that can be described as social or psychological, on how the built environment and nature impact the psychological well-being (Amirbeiki Tafti, Rezaeian, and Emadian Razavi 2018; Essawy, Kamel, and Elsawy 2014; Hartig et al. 2014; Hinckson et al. 2017; Kjellgren and Buhrkall 2010; Koohsari, Karakiewicz, and Kaczynski 2012; Korpela et al. 2017a, 2017b; Steemers and Manchanda 2010; Stewart et al. 2016; Swami, Barron, and Furnham 2018; Tilley et al. 2017). However, only those studies that have key outcomes towards designing the future built environment, i.e. using fractal patterns or PSD, were discussed in this section.

Most of the reviewed researches' methodologies had a comparative approach; the researchers were more contingent on comparing the impact of nature and the impact of the built environment. This methodology has established and proofed the deviation, between the built environment and nature, but didn't explain the mechanism or identified the critical factors of the built environment that augment the state of mind. The recent technological progress, particularly in brain mapping, has a vital role to fill these gaps.

4.3. Neuroscience and brain mapping approaches

Over the last few decades, a marked increase in interest in understanding neuropsychological mechanisms of human behaviour has spurred an eruption of innovative methods to measure and interpret brain activities. This approach is considered more technologically advanced as it depends on sophisticated instruments to scan the human brain. According to Duffau (2011); Eberhard (2009); Gegenfurtner et al. (2017), there are different methods to map the brain structure and activity and each has a favourable purpose (Figure 4):

- Structural Imaging which provides representation of the brain structure by:
  (a) Computerized Tomography (CT): It computes several X-rays from different angles to plot a two-dimensional horizontal section of the brain (Bear, Connors, and Paradiso 2016).
  (b) Magnetic Resonance Imaging (MRI): Like the CT but instead it uses a strong magnetic field to plot at a higher resolution and more sections than CT (Duffau 2011).
  (c) Water Diffusion MRI (dMRI). This is more advanced and allows mapping of the brain wiring (Duffau 2011).
- Functional imaging techniques which can provide functional information on different parts of the brain:
  (a) Positron Emission Tomography (PET): This measures the blood flow to determine the activity of the brain tissue (Bear, Connors, and Paradiso 2016)
  (b) Functional MRI (fMRI): This is more advanced and accurate, it uses the same concept as PET but measuring the local blood flow (Duffau 2011).

More recently, there have been more advanced techniques that provide higher time resolution, faster response, and can measure the brain activity in real time (Bear, Connors, and Paradiso 2016), such as:

- Electro-Encephalography (EEG): This measures the fluctuations in the electrical signals across the brain by using sensitive electrodes placed on the subject's scalp. The electric signals are collected instantaneously from the multiple electrode locations resulting in real-time brain activity mapping (Nidal and Malik 2014).
- Magnetic Encephalography (MEG): Measures the tiny changes in the magnetic field generated by the electric current in the brain. The signals are perceived by superconducting quantum interference device (SQUID) sensors. The signals

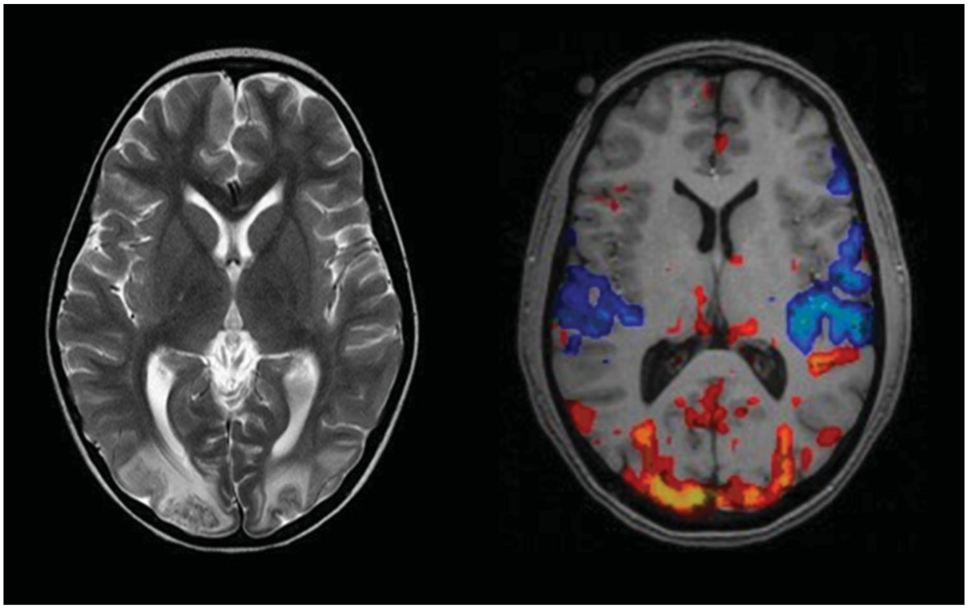

Figure 4. Comparison between MRI (left side) and fMRI (right side). The MRI image shows a static brain structure while fMRI shows different levels of the brain cell activities (Duffau 2011).

are very small (10^{-15} Tesla) so to avoid contamination, the recordings take place in a magnetically isolated room (Bear, Connors, and Paradiso 2016).

- Transcranial Magnetic Stimulation (TMS): This depends on electromagnetic induction by creating a magnetic field through the subject's skull which causes a tiny electric current in the subject's brain, simulating the neural tissues. TMS has been used generally in exploring visual perception yet it is considered hazardous and must be used with caution as it may cause seizures (Zillmer, Spiers, and Culbertson 2007).

Both MEG and EEG have a high time-based resolution and instant recording but lower spatial resolution. Therefore, for accurate structure and functional mapping, it is common to combine MEG or EEG with fMRI for high temporal and spatial resolution (Bear, Connors, and Paradiso 2016).

Most of the related studies in the literature used EEG and few used fMRI for brain mapping (Banaei et al. 2017; Hollander and Foster 2016; Shemesh et al. 2016). This could be due to the mobility of EEG and the relative lower price compared to fMRI or MEG. Among the available neuroimaging technologies EEG features excellent resolution of neural activity in the time domain, and it is considered the most reliable and predicative instrument when studying human cognition, evaluating a subject's health condition, or monitoring their mental state (David Hairston et al. 2014; Radüntz 2018).

4.4. Electro-encephalography (EEG)

EEG provides a direct measure of electrocortical activity with millisecond precision and is sensitive to changes in arousal, perception and cognitive function (Bell and Cuevas 2012). More specifically, EEG measures changes in extracellular potentials from large arrays of neurons, predominantly pyramidal cells. EEG signal patterns vary in different cognitive states according to the voltage fluctuations resulting from ion flow between neurons. The frequency of the voltage fluctuations is measured using EEG spectra (Freeman and Quiroga 2012).

The EEG signal oscillation is rhythmic; thus, it is typically described in terms of bands of different frequencies as reported in Table 2 (Duffy, Burchfiel, and Lombroso 1979; Gevins and Rémond 1987; Nuwer et al. 1999; Quiroga and Schürmann 1999) (Figure 5).

However, EEG still has several shortfalls that need further development. Firstly, Emotion Recognition techniques and software have varied accuracy; they are questionable based on the source and subjects as it is difficult to separate the cause of the change in the subject's state of mind. Nevertheless, some new methods have been developed such as Domain Adaptation Network (DAN) for knowledge transfer which showed an increase of 20% in accuracy over the traditional methods (Jin et al. 2017). Secondly, during the subjects' brain mapping many artefacts occur due to electrode movement, physical movement, optical movement and more widely reported muscle electrical activity (Islam, Rastegarnia, and Yang 2016; McMenamin et al. 2010; Olbrich et al. 2011).

4.5. Brain mapping studies in the literature

More recently, advanced research has been developed that utilizes neuroscience and brain mapping technology to accurately identify and measure the impact of the built environment on the human brain (Coburn, Vartanian, and Chatterjee 2017; Mavros, Austwick, and Smith 2016; Vecchiato et al. 2015).

Accordingly, Aspinall et al. (2015) have used EEG to compare between three different settings – green park, urban shopping area and commercial crowded space – using emotion recognition software (Emotiv). They have found that urban shopping neighbourhoods and green covered routes showed a higher level of excitement, which dropped down during a crowded commercial route. Moving from an urban area to a green area led to decreases in frustration, excitement, and engagement,

Table 2. Major Brainwaves detected by EEG and how it is interpreted (Misulis 2013; Nidal and Malik 2014).

Wave		Range (Hz)	Mental state indication	Manifestation
Alpha	(α)	7–13	Disengagement, relaxed, unwind, disentangled	They appear spontaneously in normal adults during wakefulness, under relaxation and mental inactivity conditions. They are best seen with eyes closed, most pronounced in the occipital locations.
Betta	(β)	13–30	Engagement, focused, computing	They are the best defined in central and frontal locations, with less amplitude than alpha waves. They are enhanced upon mental calculations, expectancy or tension over the entire surface of the scalp.
Delta	(δ)	0.5–4	Sleeping, unconscious	They are characteristic of deep sleep stages. Depending on their morphology, localization, and rhythmicity, delta oscillations can be normal as in slow wave sleep or pathological as in brain tumours.
Theta	(θ)	4–7	Lower Range: Unconscious, creative inspiration, deep meditationUpper range: Frustration, dissatisfaction	They are typical during deep sleep. They play an important role in infancy and childhood. In the awake adult, high theta activity is considered abnormal and related to brain disorders, such as epilepsy.
Gamma	(γ)	> 30	Attention, cognition, perception	Low Gamma rhythms (30-60 Hz in human EEG): of minor interest until the 1990s, gamma oscillations became very popular after they have been proposed to play a major role in linking stimulus features into a single perception. Several follow up works have shown correlations of gamma activity with different sensory and cognitive processes, notably during visual, auditory, somatic and olfactory perception as well as with attention.High Gamma rhythms (variously defined between 80 and 120 or above) also called epsilon rhythms have been found in both human and animal Electrocorticographic (ECoG) in association with chattering action potentials.

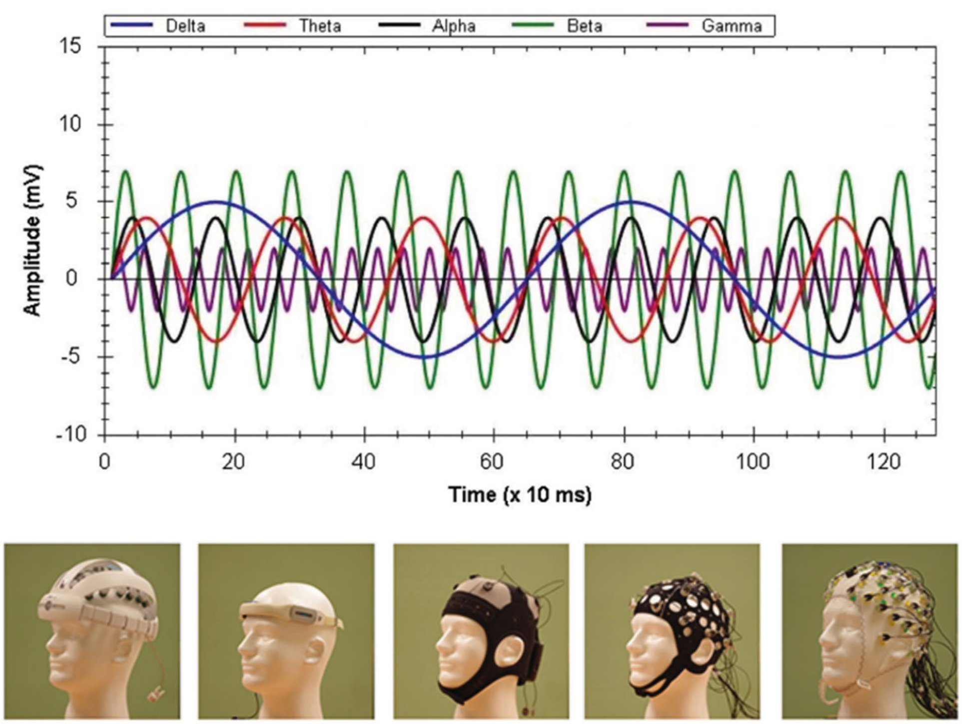

Figure 5. Top, EEG measured waves and their relevant amplitude which represent the wave length of each different brain wave (Hemeida and Mostafa 2017). Bottom, different models of EEG scanners, with different number of electrodes (Cruz-Garza et al. 2017).

whereas the meditative state increased. In contrast, moving from green area to crowded commercial areas lowered the meditation state, and increased engagement.

Shemesh et al. (2016) have combined EEG and virtual reality (VR) to measure the effect of different architectural space geometries on the human brain activity. The study indicated that brain activity occurring in the first 2 s of exposure to a specific space is critical as adaptation occurs within this period. It showed that in the first 2 s, the viewer sweeps the image and analyses it, and then only after this first 2 s stage viewers tend to focus on finer details.

Similarly, using the same combination of VR and EEG, Banaei et al. (2017) compared 69 different VR-rooms representing 17 different clusters of interior-design/architectural style. They outlined significant differences between the impact of linear and curved geometries on brain activity. Rooms associated with

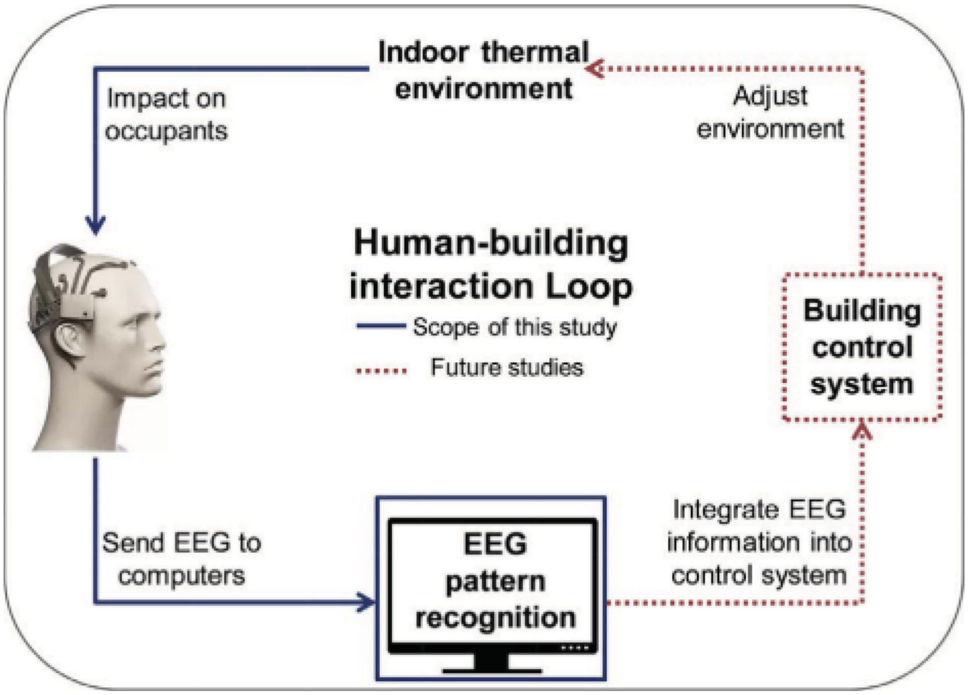

Figure 6. EEG-based methods as a feedback mechanism of occupants to improve the human building interaction, adopted from Shan et al. (2018).

lower pleasure and arousal ratings (lower anterior cingulate cortex activity) contained more linear geometries, while rooms with higher pleasure and arousal ratings (higher anterior cingulate cortex activity) contained more curved geometries. This study is inline with and confirms the same results of Vartanian et al. (2013) where fMRI was used instead of EEG.

Another study by Banaei et al. (2015) has used EEG to investigate the human brain activity while walking on two different trails in the city. The EEG results showed that the subjects were more relaxed with lower arousal levels and less anxiety; had higher alpha activity during the first 3 min of the park trail, however, this state faded after 3 min.

Investigating a different scale of the built environment – the urban scale – and using EEG, Karandinou and Turner (2018) studied the relationship between the change of the built environment surrounding the subject and their brain activity. While navigating through different urban routes, subject's wore portable EEG devices. They concluded that brain activity is much more engaged and complex, with higher beta activity indicating the interest of the subject, in the outdoor urban spaces in comparison to the indoors of buildings (Aspinall et al. 2015).

In a similar study, Hollander and Foster (2016) compared walking between two different neighbourhoods with 10 participants wearing portable EEG monitors. The result showed that participant's brain activity had a higher state of relaxation (Alpha waves) in residential areas than in business areas. It should be mentioned that in this study, the EEG device had only two electrodes which indicate lower resolution and accuracy.

More recently, and in the latest proceedings of ANFA (ANFA 2018), there are several reported and ongoing studies that used EEG for different investigations of the built environment. With a focus on the change in brain waves corresponding to different architectural designs; Zakaria Djebbara has investigated the impact of moving between two spaces with different dimensions while wearing an EEG device. Turk et al., have combined the EEG scanning of the future users with a functional building (a middle school) to increase concentration, focus and cognitive brain activity within the building. Ergan et al., have tested the impact of different interior designs on the motivation to work and they concluded that stimulating environments can increase the arousal levels by 19%.

In all the reviewed literature there were few related studies (Choi, Kim, and Chun 2015; Shan et al. 2018) that have attempted to link the Indoor Environment Quality to the state of mind. Shan et al. (2018) used EEG to enhance human building interaction under various indoor temperatures. Correlations between EEG and subjective perceptions/task performances were experimentally investigated. They tested the subject feedback (in questionnaire form) against three different temperatures: 23°C, 26°C, and 29°C. The result was compared against the EEG readings to identify the brain wave patterns against the subject's thermal feeling (warm, cold, etc.). They have used these parameters to build a machine learning-based EEG pattern recognition mechanism, as shown in Figure 6, which is based on their EEG readings, of several tasks, performed by the participants, in different conditions. Shan et al. (2018) reported that a neutral thermal condition (26°C) led to more positive emotion than the other two thermal conditions (23°C and 29 °C) which were similar. The EEG recorded waves were related to the thermal acceptability in the subjective questionnaire.

In another study, focused on IEQ, Choi, Kim, and Chun (2015) have examined the effects of the indoor environment on stress levels. Temperature, odour irritants and sound were selected as environmental elements to be studied within the combined environment and were individually controlled in a total of 12 combined environments, within a climate chamber. Experimental results indicate that occupants' stress levels were maximized when they were exposed to a temperature of 30°C, odour irritants (VOCs) and to road traffic noises.

These studies have been consistent with the results of the mentioned studies cited in Section 4.2 proving the variations of brain activity when changing the surrounding environment, more precisely the deviation of the impact of natural surroundings versus the built environment on the state of mind. The literature did show a decline in research relating to brain mapping methodology, especially in fMRI and other mapping methods. However, in general all the studies had consistent results and some studies have validated their results using the two earlier mentioned approaches.

4.6. Combination of brain mapping and psychological studies

Two of the mentioned studies have used psychological tests along with brain mapping to validate their result (Shemesh et al. 2016; Tang et al. 2017). There was no variation in the results between the psychological and the brain mapping results.

Tang et al. (2017) used functional Magnetic Resonance Imaging (fMRI) to compare the impact of different landscapes (urban, mountain, forest, and water) on the regional brain activity. The brain mapping indicated different responses to urban and natural environments. In the visual and attentional areas in the brain, especially in the 'urban versus water' landscape comparison, the right cingulate gyrus and left precuneus were activated. These regions are known as the dorsal posterior cingulate cortex and are assumed to influence the focus of attention by adjusting whole-brain metastability (Hagmann et al. 2008).

Nevertheless, it should be mentioned that in Tang et al. (2017) there was no difference in the brain activity regions when comparing urban versus forest environments. According to this finding, the brain response upon viewing urban and forest images was similar but this was not reflected in the psychological results.

In conclusion, all reported studies have proved that the change of the surrounding environment has a direct impact on human state of mind. All reviews have demonstrated a variation of the measured brain waves (Alpha, Beta, Delta, Theta and Gamma), or a change in the physiological or psychological features, while viewing or navigating different environments. These findings, even varied in their focus, collectively showed that the built environment directly impacts how the human brain is shaped.

5. Analysis of the reported studies

The research outlined in Section 4 had a variety of scope and methodologies. In general, there was no contradiction between the brain mapping results in the literature; all the studies have shown a change in the different waves corresponding to engagement, excitement, relaxation, etc. when changing the surrounding environment, especially from an urban to a natural environment.

Overall, the main features of the reported studies are comparative, with no depth into the mechanism of the impact, or identifying the critical factors of the built environment that augment the state of mind; such as determining an element (colour, scale, shape, etc.), that has a direct impact on the brain. Also, there is a lack of investigating the different features of the built environment, e.g. comparing different architectural designs to identify the main features that lead to healthier brain activity or the contrary. This represents the leading research gap which needs to be addressed in order to shape any guidelines or design recommendations for healthier built environment. As shown in Figure 7, most of the studies can be categorized into five main research focuses with no depth or detail on the design features or the mechanism of the impact.

In the reviewed literature; only few studies, summarized in Table 3, were based on accurate measurements and brain mapping tools. Those studies, even with the mentioned remarks on their methodologies, have shown a constant variation in the measured brain waves.

There are a few research efforts not reported in this section due to their focus on different aspects of the built environment such as navigation and decision making in urban areas (Erkan 2018; Juliani et al. 2016; Li and Klippel 2014; Vecchiato et al. 2015) These studies acknowledged that unique designs and landmarks are critical elements for spatial recognition. Similarly, there were few research interests that focused on the thermal comfort and its impact on the user's mental state (Choi, Kim, and Chun 2015; Shan et al. 2018).

The highest research focus, with 60% of the reported studies, is Urban scale. This is because few published studies have tried to compare nature trails with built environment trails, building on the previously mentioned theory 'Attention Restoration Theory (ART)'. This was also reflected on the significant output of the urban scale studies, as shown in Figure 7, which is relatively low because of the similarity of reported research in this focus.

As highlighted in Table 3 and Section 4.5, most of the studies used EEG for brain mapping. There is no literature that combined EEG with another brain mapping instrument to add more detail to the results. The declined number of approaches and research methodologies is also reflected in the focus of the reported research, as shown in Figure 7. The significant impact of the reported research has declined as only few studies have identified key elements that have a direct impact on the change of the human brain waves.

One general consideration, for all the reported studies, is the separation of stimuli. For example, in all fMRI studies, the fMRI scanner is noisy and it can impact the subject's state of mind (Roberts and Christopoulos 2018). Likewise, in all the EEG studies in the outdoors, there are many other stimulants that could affect the state of mind like noise, odour, navigation, physical fatigue and walking which impact the EEG signal and requires further processing to ensure the accuracy of the signal attribution.

Similarly, the detection and removal of artefactual activity that often contaminates the EEG results is not reported in the studies. During a subject's brain mapping, many artefacts occurs due to electrode movement, physical movement, optical movement and more widely reported; muscle electrical activity (Islam, Rastegarnia, and Yang 2016; McMenamin et al. 2010; Olbrich et al. 2011). Although there are several studies in the literature for effective detection and filtration of the EEG signals (Islam, Rastegarnia, and Yang 2016; Kumar, Sharma, and Tsunoda 2017; Weiss et al. 2017), the reported brain mapping studies did not elaborate in detail on the isolation of muscles' electrical activity,

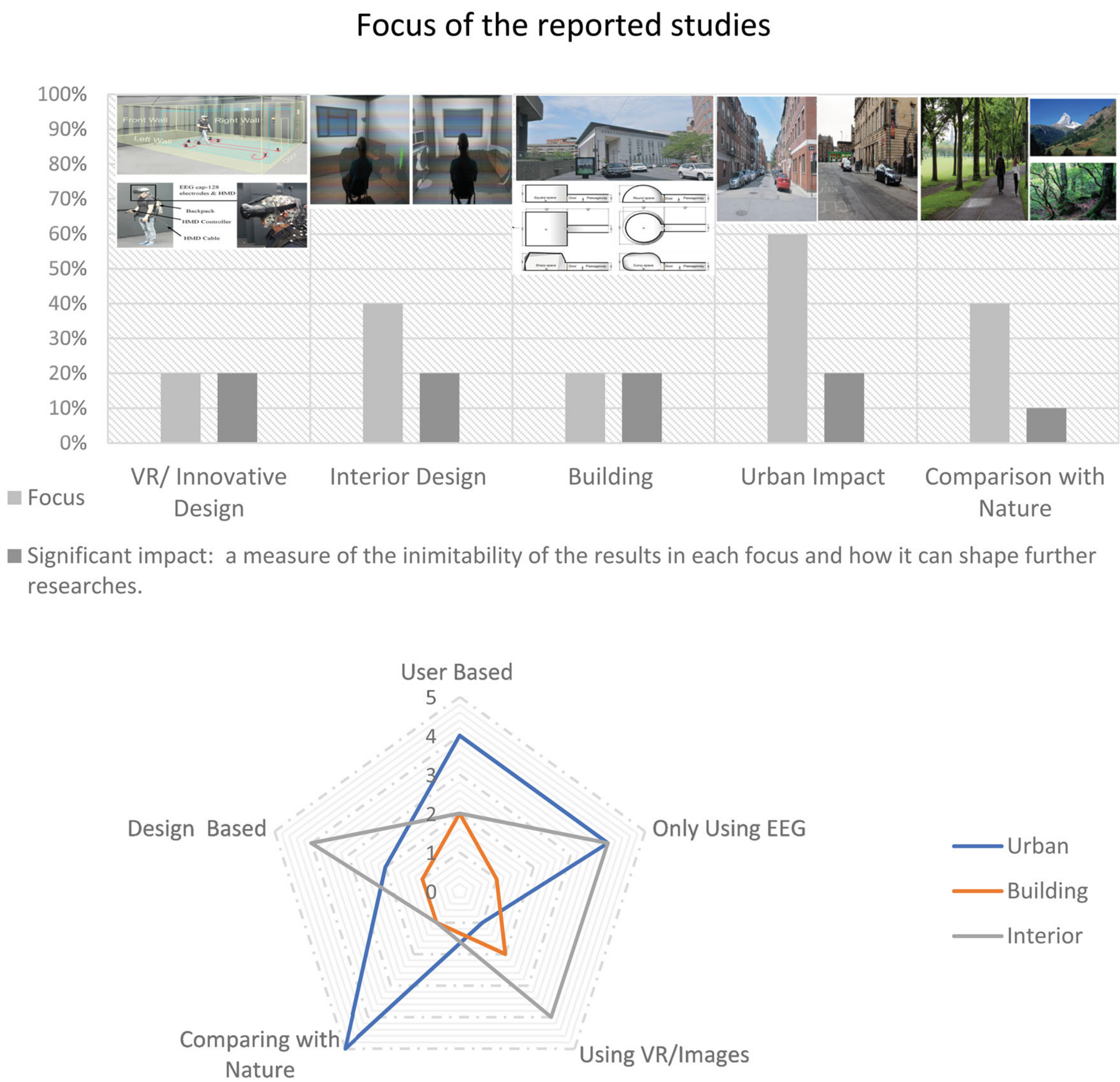

Figure 7. Top, the focus scale of the mentioned brain mapping studies. Bottom, the volume of each different subject of the built environment in the reported studies. These graphs are based only on the reported studies in Table 3; Brain mapping studies. Images adopted from: (Aspinall et al. 2015; Banaei et al. 2017; Hollander and Foster 2016; Shemesh et al. 2016; Vecchiato et al. 2015).

as most of them involved physical movement or at least optical movement. Finally, raw EEG signals are normally weak with very low amplitudes and are generally contaminated by artefacts and noises. Therefore, pre-processing of these raw signals is mostly carried out to remove such contaminations (Kumar, Sharma, and Tsunoda 2017).

Further comprehensive approaches are required to isolate each stimulus, i.e. design elements, to accurately detect the impact of the surrounding environment on the subject's state of mind. Considering the human factor and the sensitivity needed to measure complex brain activity, highly advanced and detailed research efforts are required that might even go for decades and necessitate a global database, such as the 'Human Brain Project' (Amunts et al. 2016). Further interdisciplinary research projects involving new emerging sciences and methods is required to identify the impact of each element of the built environment on the human brain, e.g. using machine learning methods to classify the emotional state of EEG readings (Wang, Nie, and Lu 2014).

6. Discussion and conclusion

The human brain has more invigorating brain activity, indicated by EEG, when in the natural environment (Zhang, Howell, and Iyer 2014). There are even some theories that claim an evolutionary root of attraction to the aesthetic nature and how it enhanced our chances of survival (Dutton 2009; Etcoff 2011). Moreover, current urban planning practices already uses nature settings and parks for their impact on the brain (Qin et al. 2013).

Winston Churchill said 'We Shape our buildings; Thereafter they shape us' (Brand 1995). However, during the architectural design process, there is negligible consideration to the impact of the built environment on psychological well-being and mental health (Goldhagen 2017). Although in the current engineering codes and green rating/certification guidelines such as, LEED (LEED 2017), BREEAM (Global 2016) or Green Star NZ (Doan et al. 2017), there are many regulations regarding indoor air quality, natural light exposure, etc., that promote a healthy environment, there is no regulation or guideline towards mental health

Table 3. Summary of the research studies based on brain mapping.

Study	Instruments	Investigation	Key findings	Remarks
Tilley et al. (2017)	• EEG • Interviews	Compare the Urban vs. natural environment.	A positive effect of green space. Higher engagement and excitement (Betta waves) and lower levels of frustrations (upper Theta range).	Small sample, only 8 subjects were able to complete the two parts of the research.
Shemesh et al. (2016)	• EEG • VR • Questionnaires	The effect of different architectural space geometries.	The first two seconds of exposure to space are critical to brain adaptation.	The VR spaces are empty and don't represent the actual real built environment.
Karandinou and Turner (2018)	• EEG	Navigation in different urban roots.	Higher brain activity in the outdoors urban spaces.Beta waves are increased when encountering people.	The rout of the journey was not fixed which involved the subject to make navigational decisions.
Hollander and Foster (2016)	• EEG	Walking within two different neighbourhoods; residential vs. business.	More comfortable in the residential than in the business neighbourhood.	The EEG device had lower resolution and accuracy.
Banaei et al. (2015)	• EEG	Walking on two different trails; Park vs. commercial.	Lower arousal levels and less anxiety during the first 3 min on the park trail, more excited on commercial trail but this state faded after 3 min.	The commercial trail was a historic attraction.
Aspinall et al. (2015)	• EEG	Comparing green park, urban shopping areas and commercially crowded spaces.	Urban shopping areas and green routes showed a higher level of excitement.Moving from green to crowded commercial: meditation state dropped, and engagement increased.	The study is based on twelve students without background diversity.
Banaei et al. (2017)	• EEG • VR	Comparing 69 different VR-rooms representing 17 different clusters of architectural style.	Rooms with higher pleasure and arousal (Theta waves)ratings contained more curved geometries.	The study is based only on VR experience.
Essawy, Kamel, and Elsawy (2014)	• EEG	The impact of spiritual buildings on the human brain.	Higher state of relaxation and calm awareness (Alpha waves) when staying inside the buildings.	Only a three-electrode EEG device was used.
Tang et al. (2017)	• fMRI • Questionnaires	Comparing urban, mountain, forest, and water environments.	Different response to urban and natural environments especially water landscapes; right cingulate gyrus and left precuneus were activated.	No difference in the brain activity regions when comparing urban versus forest environments.The study was based on viewing images only[a].
Vartanian et al. (2015)	• fMRI	Ceiling height & open vs. enclosed spaces	Higher ceilings & open spaces are more attractive.Enclosed spaces more avoided by the subjects.	The study is based on viewing images[a].
Vartanian et al. (2013)	• fMRI	Comparing rectilinear and curvilinear interior spaces.	Curvilinear spaces activated the aesthetic processing part of the brain.	The study is based on viewing images[a].

[a] All fMRI studies are based only on viewing of images not on real-time full experiences. This is due to the complexity and size of the scanning machine. However, fMRI offers more structural mapping and higher spatial resolution as mentioned in Section 4.2.

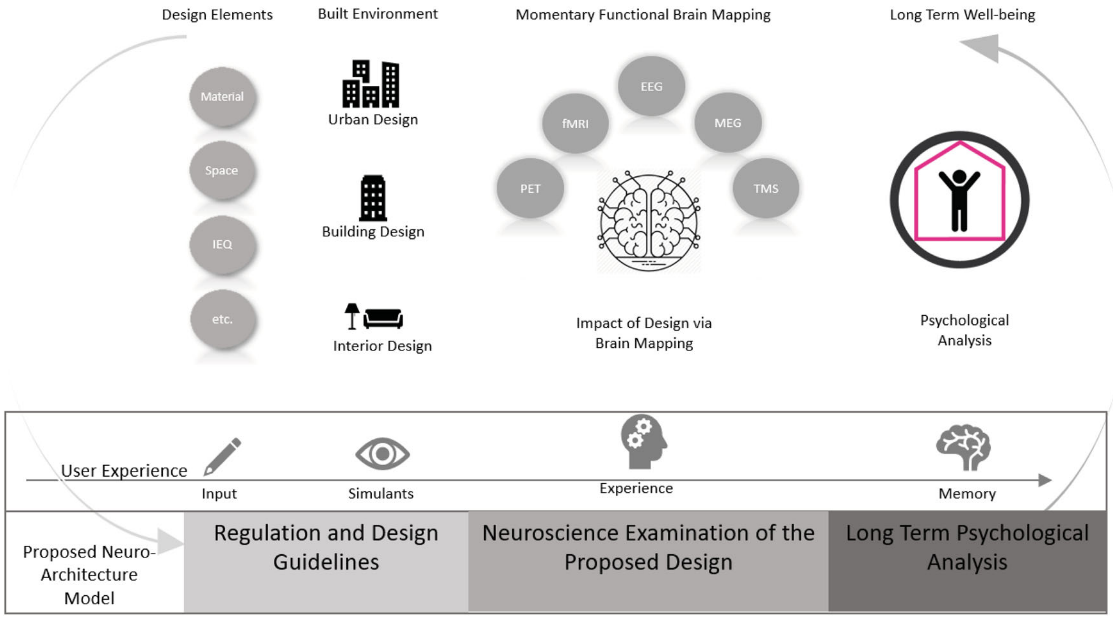

Figure 8. The different scales of required research to understand the impact of the built environment on the human perception, with proposed procedures to include the user's wellbeing in the design process.

or the impact of the built environment on the brain. In current urban planning practices, mental health has been neglected even through smart design solutions to avoid traffic or to ensure high quality of urban settings that would positively impact our psychological well-being (Bornioli, Parkhurst, and Morgan 2018; Kjellgren and Buhrkall 2010).

The only related guidelines that mention the impact on the neural system were found in WELL building standards (IWBI 2017a):

> The WELL Building Standard places the utmost importance on supporting neurologic and cognitive function through a variety of interventions. Features work to limit the exposure to environmental toxins in air and water, encourage balanced diets and optimal levels of physical activity, and enhance sleep quality and mitigate stress through the implementation of a variety of comfort measures.

Most of the mentioned measures are similar to LEED, BREAM and Green star NZ. The only additions are the promotion of eccentric and mindful designs, without any specific design elements and features, and the requirement for a mental health care facility within a 1.6 km (1 mile) walking distance of the community boundary (IWBI 2017b).

This lack of specific regulations or guidelines is critical and needs to be addressed, as mentioned before the average time spent in the built environment is 90% of the lifespan. This portion of our lifespan is critical in forming our perception and it magnifies the relationship between the built environment and our psychological well-being. The future research must investigate the different levels of human interaction with the built environment to better understand the impact on the human brain, see Figure 8.

The central research gap is that the reported studies have limited significant outputs. They mostly focused on proving the impact of the built environment but have no detailed research with a precise focus on a single design element to investigate the mechanism or to identify a specific feature of the built environment. Even though several studies have reported a deviation between the built environment and natural restorative surroundings, the cause of such deviation was not exploited as the highest percentage of the reported studies are comparative. There was an evident shortage of investigating the mechanism of the human perception for the built environment, hence, as highlighted in Section 5, the reported studies had declined critical findings that can benefit the future built environment. This lack of input to the designers and decision makers is vital to address any regulations or standards that could improve the human experience within the built environment.

Although, the deep engagement between people and the built environment makes empirical research very difficult. For example, certain spaces or even colours can trigger many memories and feelings which vary extremely in humans as the research subject. This relationship complicates the measurements of the specific experience and how it impacts the brain, directly or indirectly. Therefore, the integration of psychology and neuroscience experts in any empirical study is critical to abstract the impact of certain design features on the human brain (Coburn, Vartanian, and Chatterjee 2017).

However, the idea of an interactive built environment that keeps the user engaged and excited is not fictional. In 2002 at the Swiss Expo.02, Ada-an intelligent interactive space-was represented. The space was visited by over half a million visitors. The space was designed to interact with several users through light and sounds to keep them engaged (Arbib 2012; Eng et al. 2003). With the recent advances in newly developed science, such as Bio/Neuro-Informatics and the implementation of new machine learning methods and analysis for user's brain mapping data, buildings could be customized to the users mental state (Arbib and Grethe 2001; Hassabis et al. 2017; Kasabov 2013; Kasabov 2019). Such innovative approaches can lead to more explicit identification of the user experience in the built environment.

In conclusion, all the reviewed literature was consistent in signifying the variation of the impact of the built environment, and the impact of the evolved nature on the measured human brain waves. Using accurate scientific measures, such as fMRI and EEG, showed positive impacts on the human brain while in natural settings. On the contrary, the built environment has exhibited higher frustration and stress level as indicated by the measured brain activity. While there is a growing desire to document how the brain/mind reacts to different environmental stimuli and how that may benefit the field of architecture, engineering, and landscape design, very little is known at this time.

There was only few design elements that was identified in the literature, i.e. curvature as an alternative to straight lines, which has a direct relation to brain activity (Banaei et al. 2017; Vartanian et al. 2015; Vartanian et al. 2013). Even though we can argue their use of VR or fMRI with only photos, these research efforts are considered having a significant impact, as they presented a direct input to designers that interior designs with more curvatures, higher ceilings and less straight lines showed higher excitement and engagement levels. Similar critical studies are required on a bigger scale, e.g. building designs and urban planning, to identify which features to include or exclude in the built environment regulations.

Only few studies have examined different urban designs with various functions, e.g. residential vs commercial, and their varied impact on the human state of mind (Aspinall et al. 2015; Hollander and Foster 2016). This inclusion of the buildings' functions into the human measured experience is critical to identify the impact of the built environment on the human brain.

The reviewed litrerature has proved that a built environment with positive effects on the human brain can be reached by (1) Encouraging more research with advanced focus and specific scope into the mechanism and the design features; (2) More detailed research to simulate nature in the built environment; (3) Innovative designs with instant brain activity measurements that could link the building function with the measured state of mind. These might open the way to healthier surroundings that have positive impacts on the brain which will lead, in the long term, to psychological well-being.

Disclosure statement

No potential conflict of interest was reported by the author(s).

ORCID

Sameh Azzazy http://orcid.org/0000-0003-3076-5269

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