Journal of Environmental Psychology 66 (2019) 101344

Contents lists available at ScienceDirect

Journal of Environmental Psychology

journal homepage: www.elsevier.com/locate/jep

Impact of built environment design on emotion measured via neurophysiological correlates and subjective indicators: A systematic review

Isabella Bower[a], Richard Tucker[a,*], Peter G. Enticott[b]

[a] School of Architecture and Built Environment, Faculty of Science, Engineering and Built Environment, Deakin University, Victoria, Australia
[b] Cognitive Neuroscience Unit, School of Psychology, Faculty of Health, Deakin University, Victoria, Australia

ARTICLE INFO

Keywords:
Environmental enrichment
Environmental psychology
Emotion
Interior design
Built environment
Neurophysiological measures

ABSTRACT

Studies investigating environmental enrichment have shown that exposure to enhanced sensory, cognitive, motor and social stimulation results in behavioural, cellular and molecular alterations in animal models. However, the evidence-base for the neurophysiological impact from environmental enrichment in humans has not been widely examined. This paper, which considers the built environment as one significant component of environmental enrichment, draws together evidence on the impact of the design of interior spaces on human emotion.

With no robust models currently available to evaluate how built environment design impacts our emotional states, this systematic review consolidates research that has measured correlates of emotion in interior settings using measures recording either autonomic nervous system (ANS) and/or central nervous system (CNS) activity in conjunction with self-reporting to indicate conscious perception. This paper aims to assess what we know, what methodologies exist and if consistencies can be seen across previously published studies.

The review found 237 records, of which 16 met abstract selection criteria. Only seven studies (across eight papers) met full-text selection criteria. Due to the vast differences in the methodologies applied, a comprehensive synthesis was not possible; highlighting the gap in controlled studies in this field of research.

As Post Occupancy Evaluations (POEs) of the built environment currently focus on the physical safety and environmental performance of buildings, this review helps inform the techniques and protocols that can be applied when evaluating the emotional effect of built environment exposure.

1. Introduction

Our understanding of how the design of the built environment affects our emotion is not well understood (Eberhard, 2009; Nanda, Ghamari, Pati, & Bajema, 2013). With increasing mental health issues in the population (AIWH, 2018), and lifestyles where substantial time is spent inside of buildings (Klepeis et al., 2001), it is important to empirically determine whether exposure to the built environment is affecting our emotional states. If so, would this emotional response affect our overall mental health and sense of wellbeing? The aim of this systematic review was to establish if the current body of research has shown evidence linking the built environment to altered emotional states. From this, we aimed to understand how we can evaluate the impacts that interior built environments have on emotion, and thus whether it might be possible to increase positive emotions through building design to aid the health and wellbeing of the population.

For over 50 years, researchers from various fields have sought to understand how the characteristics of the built environment impact our emotions, behaviours and, more recently, our physical well-being. Until recently, much of this work has occurred within disciplinary silos. However, increasing numbers of convergent teams between Humanities, Arts and Social Sciences (HASS) and Science, Technology, Engineering and Medicine (STEM) are forming to bring inter-disciplinary and industry expertise to this field of research.

Neuroscientists have long investigated the concept of environmental enrichment (EE). In EE experiments, animals are exposed to a housing condition that provides opportunity for enhanced sensory, cognitive, motor and social stimulation. The EE condition, in comparison to neutral housing conditions, has been found to result in significant behavioural, cellular and molecular alterations as well as disease offset in some neurological conditions (Nithianantharajah & Hannan, 2006; Van Praag, Kempermann, & Gage, 2000). It has been suggested that this is

* Corresponding author. School of Architecture and Built Environment, Faculty of Science, Engineering and Built Environment, Deakin University, Geelong, Victoria, 3220, Australia.
E-mail address: richard.tucker@deakin.edu.au (R. Tucker).

https://doi.org/10.1016/j.jenvp.2019.101344
Received 25 January 2019; Received in revised form 1 August 2019; Accepted 31 August 2019

because enriched environments cause higher levels of brain activation, leading to molecular changes for neuronal function and neuroplasticity (Fox, Merali, & Harrison, 2006). Despite these indicators of positive effects on brain development and health, the translation of EE in human models remains an under developed field of research due to the complexity of the environmental exposures that humans experience (Clemenson, Deng, & Gage, 2015; McDonald, Hayward, Rosbergen, Jeffers, & Corbett, 2018; van den Bosch & Bird, 2018).

Numerous studies in the social sciences have explored whether built environments impact our psychological health (G. W. Evans & McCoy, 1998; Ferguson & Evans, 2018; Papale, Chiesi, Rampinini, Pietrini, & Ricciardi, 2016). However, this field of enquiry has predominately used subjective indicators of psychological effect through self-evaluated rating scales, questionnaires and descriptions (Dazkir & Read, 2012; Dinis et al., 2013; Küller, Ballal, Laike, Mikellides, & Tonello, 2006; Roessler, 2012). While subjective indicators are important tools for understanding perceived experience, it is suggested that the subjectivity of human consciousness makes it difficult to compare, quantify and justify this impact (Edelstein & Macagno, 2012). Adding to this difficulty, it is well established that our bodies are able to respond to a stimulus before we are able to consciously process the input (Öhman, Flykt, & Lundqvist, 2002), and in some circumstances without involvement of the visual cortex. For example, 'blindsight' lesion patients showed brain activity, consistent with recognising facial stimuli depicting fear, without conscious visual experience of the stimulus (Liddell et al., 2005). This stimulus response lag leaves a gap in subjective self-reported evaluation as the brain experiences extensive physiological activity prior to and during effortful cognition processing (e.g., determining subjective indicators).

The term 'behaviour setting' emerged from the field of environmental psychology to describe the effect of the physical environment (time, place and objects), as well as the social environment (activity patterns of others), on behaviour. (Barker, 1978). Behaviour settings were understood to be often bounded by architectural space (Bechtel, 1977; Schoggen, Barker, & Fox, 1989). Explaining the relationship between emotion on behaviour, Lazarus suggested that an emotional response occurs from appraisal of the personal significance of an event, and that this response results in changes to subjective experience, the peripheral/autonomic nervous system, the central nervous system and thus to behaviour (Lazarus, 1991).

Built environment impacts on emotion can also be suggested via the social interaction impacts of the built environment. But while the impacts of social factors on social interaction have been widely considered (Francis, Giles-Corti, Wood, & Knuiman, 2012; Fried, 1982; Sampson, Morenoff, & Gannon-Rowley, 2002; Skjaeveland & Garling, 1997; Unger & Wandersman, 1985), far fewer studies have considered the impact of the physical characteristics of the built environment on social interaction beyond the single variable of density (Arundel & Ronald, 2017). Moreover, while neighbourhood differences in social connectivity have been mapped, few empirical studies have considered the interplay between social interaction and specific physical characteristics of the built environment. Thus, for instance, it remains poorly understood how proxemic relationships impact the experience of design characteristics.

Although design practitioners and researchers have long argued that the places we inhabit, whether urban landscapes, buildings or natural environments, directly affect our behaviour (Altman & Wohlwill, 1976), we are still yet to objectively determine the effect of these physical contexts on emotion. However, through the rapid progression of science and technology, researchers can now use biomedical techniques to elucidate objective evidence of emotion-related neurophysiological impact. In response, studies using novel measures such as electroencephalography (EEG) (Mavros, Austwick, & Smith, 2016; Roe, Aspinall, Mavros, & Coyne, 2013) to measure electrical activity, and functional near infrared spectroscopy (fNIRS) to measure cortical oxy-/deoxy-genation of haemoglobin as a correlate of neural activity (Tsunetsugu, Miyazaki, & Sato, 2005), have emerged as multi-disciplinary research teams race to explore the emerging neuroscience behind our experience of architecture.

Studies using objective measures to evaluate buildings have focused on comfort variables as indicators of building performance (Dewing, 2009; Ma, Wong, & Mak, 2018; Parkinson & De Dear, 2016). Comfort variables, commonly referred to as Indoor Environmental Quality (IEQ), include thermal comfort, lighting, humidity, airborne contaminants, acoustics, airflow and ventilation. Research investigating the impact of IEQ variables on building performance and occupant satisfaction has demonstrated significant effects. The use of such an objective measurement system arises from an understanding of the accepted range for human physiological comfort. While it is understood that the IEQ performance of space has a significant effect on emotion (Kim, Chong, Chun, & Choi, 2017; Steinmetz & Posten, 2017) (e.g., being comfortable is important for optimal functioning), few studies have controlled IEQ in their experimental design to independently analyse the impact that design characteristics such as colour, shape, texture and scale have on emotion. This limitation raises significant concern for the quality of research when IEQ factors may have confounded the results. It is also notable that there has been a gap in translating the controlled environmental conditions from animal studies used in neuroscience into the human environment research field.

While studies have shown that design characteristics impact self-reported emotion, and that IEQ can further affect physiological emotion response, a further dimension is offered by the addition of other inherent qualities of built environments, such as context driven cue reactivity (Chiamulera et al., 2017), and proxemics between occupants that trigger a range of outcomes hard to control or predict (Gary W. Evans, Schroeder, & Lepore, 1996). In addition, evidence suggests emotions can directly impact health by affecting the immune systems inflammatory response and indirectly alter health related behaviours, thus further diminishing wellbeing. For instance, negative emotional states influence disease aetiology and cascade to reduced social interaction, physical activity and compliance with healthcare advice as a secondary effect on overall wellbeing (Kiecolt-Glaser, McGuire, Robles, & Glaser, 2002). Due to the extensive periods of time we spend within interior built environments and our inherent interaction with them, it is critical the link between design characteristics of the built environment and emotional states is understood.

Focusing on interior spaces, this review assesses the effects of design characteristics (of physical or virtual interior spaces) on the emotional states of both healthy and clinical populations. The research focused on interior built environments due to difficulty with controlling for the multitudes of external factors (e.g. climatic and weather events) that make up the experience of exterior space. By reviewing and synthesising current knowledge, the review establishes if neurophysiological markers of emotion can be used to distinguish emotional states, and whether these markers align with consciously perceived self-reported responses resultant from exposure to controlled, enclosed interior built environments. It is hoped that through this understanding the design of the spaces we inhabit can be optimised to support physical and psychological health and wellbeing, thus contributing to preventative mental health care.

Screening revealed 16 papers derived from 14 studies for full text review. Independent full-text review by two authors agreed that only eight (from seven studies) of the 16 papers met the criteria of having used objective and subjective measures, within a semi-controlled virtually or physically experienced built-environment, to evaluate the impact of design through measuring correlates of emotional response.

It is evident from the limited studies available there is a need for more research to elucidate how design variables of the built environment affect human emotion. The eight papers reviewed reported that their experimental approach verified that exposure to one or more elements of a virtually or physically experienced interior-built environment impacted emotional states under varying types of controlled conditions. It was found that all studies lacked variance in cultural background and age groups of participants. Moreover, no studies meeting the inclusion criteria had evaluated the impacts of colour, or proportion. In these eight studies, four design variables were investigated: (1) form (3D) or geometry (2D), (2) materiality or texture, (3) style and context of interior furnishings, and (4) the ceiling height/sense of enclosure of the space.

2. Background

2.1. Description of the condition

In this review, affect and emotion are considered as separate terms, such that affect is a general umbrella term for the sense of bodily state (particularly with respect to the detection of valence and arousal), while emotion is defined from a neurobiological perspective as a complex reaction involving, in part, stimulus processing in both subcortical (e.g., limbic) and cortical brain networks, along with a complex mental representation (Lee & Hsieh, 2014). Correlates of neurophysiological emotion can be measured through the non-invasive methods, such as electroencephalography (EEG) to observe electrical activity from brain signalling, as well as through functional magnetic resonance imaging (fMRI), and near infrared spectroscopy (fNIRS) (both fMRI and fNIRS detect changes in blood oxygenation, which is taken to indicate recent neuronal activity). Other physiological indicators indicating arousal to a stimulus include heart rate, blood pressure, breathing rate and galvanic skin response (GSR) also known as skin conductance resonance (SCR). This review examines studies that measure emotion in participants exposed to virtually or physically experienced built environments through a combination of techniques indicating ANS and/or CNS response as well as conscious perceptions.

2.2. Description of the intervention being investigated in this review

Built environments are tangible human-made interventions that enclose space and provide the setting for human activity. This review examines studies investigating how design elements that comprise the built environment impact neurophysiological emotion.

This research chose to limit study designs to interior built environment settings as a result of the significant proportion of time humans spend indoors and the complexity of variables that make a controlled experiment difficult to achieve in external environments. The study is confined to semi-enclosed spaces; defined as confined on both sides of a vertical axis (floor and ceiling) and on at least three of four sides on the horizontal axis. If the space has more than four sides or has curvilinear surfaces, the space is considered semi-enclosed if the field of vision of the inhabitant is contained by solid matter. The review includes studies using virtual reality to control how participants are exposed to experimental conditions e.g., using a Cave Automatic Virtual Environment (an immersive space created through projecting the virtual space onto screens surrounding the participant), or where a stereoscopic head mounted display is worn.

2.3. Why is it important to do this review?

To understand how and if the built environment plays a role in our psychological and physiological wellbeing, we must consolidate evidence across fields. This review explores what methods are currently used to measure emotional state and whether these studies indicate that exposure to built environment features alter neurophysiological markers of emotion and self-reported responses in healthy and clinical populations. A systematic review of this kind comes at a critical time as our population is rapidly expanding, mental health issues are growing and technological advancements for objectively measuring physiological responses to stimuli are progressing. As a result of the widescale impact the built environment may have on our health, this review can be important for policy makers and built environment practitioners.

If we can demonstrate that objective neurophysiological markers of emotion can be measured from exposure to the built environment, then subsequent guidelines and design standards could aim to significantly improve public health. This review will enable us to understand how thoroughly this field of research has been investigated, by whom, where in the world and what methodologies for measuring emotion currently exist.

3. Material and methods

3.1. Criteria for considering studies for this review

The authors utilised the methodology provided in the Cochrane Handbook (Higgins & Green, 2011) to perform the steps required in this systematic review.

3.1.1. Types of studies

The review focused on studies where subjects were: (1) exposed to a control and treatment condition/s, and (2) reported either ANS and/or CNS response in conjunction with a form of self-report on emotional state. For example, where (1) exposure to a specific design component, such as colour, form, texture, scale etc., within a simulated or physically experienced built environment, and where (2) heart rate was used to determine response to stimulus (ANS), EEG was used to measure neurophysiological impact (CNS) in combination with a point scale to evaluate the self-reported emotional state of the participant. Due to the limited research available, a range of mixed methods studies that examined both objective and subjective indicators for cross-validation were sought. Randomised and non-randomised study designs were included, measuring ANS and/or CNS response, in addition to a self-reported form of emotional state data.

3.1.2. Types of participants

We have excluded animal models of 'environmental enrichment,' focusing instead on what evidence currently exists from studies with human populations. Participants included healthy and clinical populations to elucidate if impacts are different across population types. While we aimed to only include research that took a random population sample, the lack of such studies from a preliminary scoping review meant that our population was limited to participants of a certain age bracket (undergraduate university level), and/or race and/or geographical location.

3.1.3. Types of interventions

The review incorporated any study investigating design characteristics of the built environment that included, but were not limited to shape, colour, symmetry, texture, form, scale, proportion, pattern and hierarchy. We excluded studies that did not compare an intervention (such as exposure to a design component) with a neutral control/comparator. The following contexts were investigated of comparisons of intervention versus control/comparator:

- Virtually experienced through controlled Cave Automatic Virtual Environment (CAVE) projected display, where four projection screens form a room comprising of 3 walls and a floor;
- Virtual Reality head mounted display via which the participant sees an enclosed virtual interior space;
- Physically experienced (through controlled conditions) where a participant is immersed in a semi-enclosed space (such as a room).

3.1.4. Types of outcome measures

This review included all studies meeting the selection criteria that reported an objective indication of autonomic response or central nervous system activity with self-reported indicators of emotional state for cross validation. We did not limit the form of mixed methods, and thus found a variety of techniques and measurements to evaluate emotional state.

CNS measures included but were not limited to electroencephalography (EEG), electrocardiography (ECG), electrooculography (EOG), functional magnetic resonance imaging (fMRI) and functional near infrared spectroscopy (fNIRS) cerebral blood flow. ANS measures included cardiac activity including blood pressure and pulse rate, respiration rate and galvanic skin response (GSR).

Self-reported measures to indicate conscious perception included but were not limited to point scales, Likert scales, Self-Assessment Manikin (SAM) models, Profile of Moods States (POMS) and space characteristic descriptions.

The broad categories informing our content analysis of the studies are: an understanding of the effect of emotional state change from exposure to design components in the built environment; the experimental design approach; correlation between brain/body responses and consciously processed measures of emotional state.

3.2. Search methods for identification of studies

A search strategy combining the most frequently used terms (interior design AND emotion) was used in conjunction with limits that included: authored in English, peer reviewed, and records from between the years 2000 to July 2018. This timeframe coincides with when the body of significant work had been achieved in the field, which was catalysed by technological advancements and a surge of interest in transdisciplinary research. The list of final search strings (Appendix A) was refined over a period of four months in consultation with librarians from health sciences, the social sciences and architecture. A range of databases was searched across the social and biological sciences. Architecture and built environment databases (Avery Index to Architectural Periodicals and Planning Architecture Design Database Ireland) were incorporated in the preliminary search strategy but were excluded during the full review as they did not retrieve any relevant records. Three Elsevier databases were searched (EMBASE, Science Direct and Scopus) as well as: The Cochrane Systematic Review Database; MEDLINE; PsycINFO and Web of Science. During the review process, email alerts from the selected databases were employed to identify newly published studies not retrieved during the initial search.

We also searched Google and Google Scholar applying the database search keywords and limiting our screening to the first 10 pages or until the results appearing were no longer relevant. After we conducted full-text eligibility of articles, we mined the references and citations from the included studies to cross-check that important texts had been covered.

Four weeks before we submitted the final review for editorial approval, we performed an updated search on all specified database and non-database sources. At this stage, twelve additional records were found with only one record meeting selection criteria for independent full text review.

3.3. Data collection, management and synthesis

The first two authors reviewed the eligibility table before preliminary title and abstract screening. The lead author scanned the abstract and title of all retrieved records to determine which studies would undergo full-text assessment, consulting with the second author for verification. The full texts of studies meeting the selection criteria in the title and abstract screening were independently evaluated by two of the authors. Both reviewers chose to include eight of the papers representing seven individual studies. One additional paper identified four weeks prior to submission for full-text review was independently evaluated by the two authors but rejected.

A screening scoring matrix using criteria for the population, intervention, comparator/variable, outcome and setting (PICOS) was developed by the lead author. The matrix required the lead and second author to independently identify if studies met the requirements. The authors then shared their tables to compare if the same studies had been selected. The outcome was that both reviewers independently selected the same studies, cross validating the selection process.

Studies from the database and non-database sources that met the preliminary selection criteria were saved into a shared EndNote library before the full-text selection assessment was conducted.

The lead author independently extracted the study aim, country/origin, method, participants, intervention, setting, outcomes and, where required, notes detailing additional information that could influence the extracted data. The data extraction method was adapted from the Cochrane Public Health Group Data Extraction and Assessment Template. This entails extracting information on the type of study, participants, type of intervention, comparator group/s, outcome measures and setting.

The study used the Cochrane Collaboration Risk of Bias Tool (Higgins JPT, 2017) to determine the quality of the included studies. Risk of experimental bias was assessed by the lead author for each of the eight full-text articles. Findings from the bias analysis are discussed in the results. However, due to the small number of studies found for this review, no studies were excluded for risk bias.

A flow diagram outlining the selection and analysis process is shown in Fig. 1.

4. Results

Sixteen papers met eligibility in the title and abstract review; refined to seven studies (eight papers) through independent full-text screening. The seven were published between 2004 and 2017. There were two instances within the sixteen papers (four papers in question) where the same author had published two papers from one study (Vartanian et al., 2015; Vartanian et al., 2013; Vecchiato, Jelic, et al., 2015a; Vecchiato, Tieri, et al., 2015b). To determine which of these papers to include, the authors agreed to only include those papers reporting different study outcomes. This restriction resulted in inclusion of two papers from one study by Vartainian (2013 and 2015), and one paper by Vecchiato (2015a, b). Thus, eight studies were agreed upon independently by both the authors for inclusion. A latter search conducted for new studies found one extra for full-text review, but this was mutually excluded by the authors as the stimulus included exposure to exterior built environments.

The inclusion process led to the removal of 19 studies examining external or urban environments, 35 studies reporting only subjective measures, and 19 studies focused on Indoor Environmental Quality variables.

4.1. Overall results

The included studies evidenced that design characteristics of interior built environments can result in:

- Exit decisions and lowered judgement of beauty in enclosed rooms with lower ceilings (Vartanian et al., 2015);
- Lower self-evaluated ratings for pleasure and arousal in rooms with more linear geometries with decreased anterior cingulate cortex (ACC) activity (Banaei, Yazdanfar, Hatami, & Gramann, 2017) and association of curvilinear spaces as 'beautiful', which activated ACC but did not alter exit decision about space (Vartanian et al., 2013);
- Furnished interior environments received higher self-reported ratings for the emotion state dimensions of presence and arousal indistinctly of the style of furniture which resulted in increased heartrate and larger theta power across frontal sites for high presence (Vecchiato, Jelic, et al., 2015a);
- The use of stereoscopy to enable the appearance of depth in virtual environments increases self-reported levels of presence in participants (Rodríguez, Rey, & Alcañiz, 2011); and

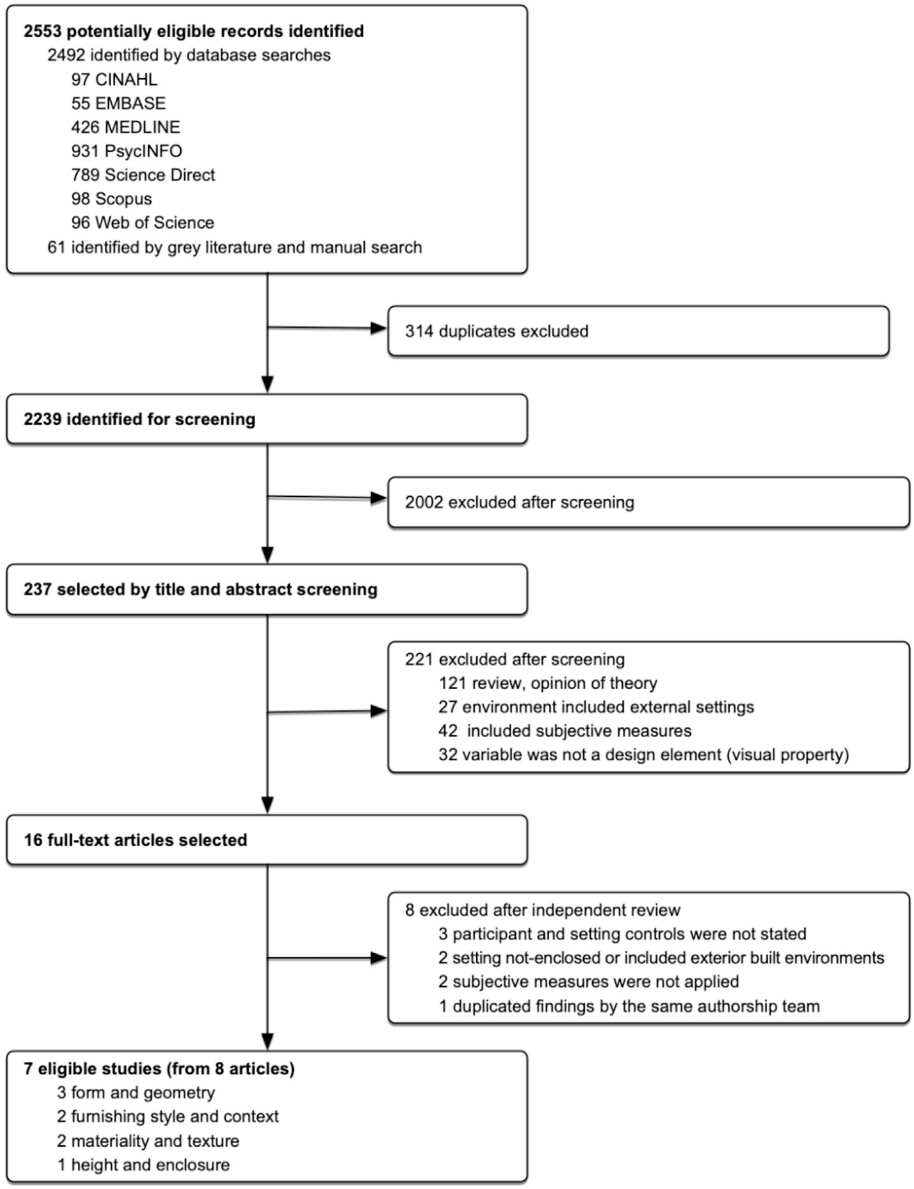

Fig. 1. Flow diagram of the article selection process following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) process.

- Materiality (wood texture) in both virtually and physically is able to reduce ANS activity (heart rate and sweat response) without conscious perception by participants (Tsunetsugu et al., 2005; X.; Zhang, Lian, & Wu, 2017).

Notable excluded studies included those where: participant and environmental controls were not stated (E. A. Edelstein et al., 2008; Elbaiuomy, Hegazy, & Sheta, 2018; L. Zhang et al., 2010); the study included examples of exterior built environments (Kirk, Skov, Christensen, & Nygaard, 2009; Pati, O'Boyle, Hou, Nanda, & Ghamari, 2016); participants were selected from the same University disciplinary cohort and did not apply a self-reported measure/s (Radwan & Ergan, 2017; Sharma et al., 2017); and the paper reported duplicated findings by the same authorship team (Vartanian et al., 2013). We also excluded one study that used a window to the outdoors and which induced stress on participants (Fich et al., 2014).

While the excluded studies offer valuable insights into the impact of built environment, this review focused specifically on controlled interior spaces not subject to climatic conditions or the complexity of natural features and phenomenon. While stress variables are important to understand, introducing stress in experimental conditions may alter brain function and the magnitude of emotional response that might occur naturally.

4.1.1. Population

During the screening process, participants were not limited to age, gender or cultural background. Overall, 122 people in total took part in the studies. Across all studies, the average age was 26 with small standard deviation (see population characteristics in Table 1). Gender mix varied between studies with only one paper (X. Zhang et al., 2017) reporting equal numbers of male and female participants. Two studies (Rodríguez et al., 2011; Vecchiato, Jelic, et al., 2015a) included odd numbers of participants with roughly equalled gender (included one more female than male). While there was a notable uneven balance of sexes in the study reported by two papers (Vartanian et al., 2015) (6 males to 12 females), the rationale for this was not described. Similarly, Tsunetsugu et al. (2005) did not justify why they included only male participants. Only one study (Shemesh et al., 2017) failed to report the gender of participants.

Inclusion criteria for participants included some which were

Table 1
The characteristics of the population and the environmental conditions reported in studies. This includes the gender breakdown, final study size, mean age of participants standard deviation of participant, method of experience (whether in a physical space or an experience facilitated through a virtual reality environment or headset), common IEQ parameters of lighting, temperature, humidity and noise and where reported and the size of the environment.

	Year	Population					Environment/Setting					
		M	F	Study Size	Age Mean	Age SD	Method of experience	Artificial lighting lx	Temp °C	Humidity RH%	Noise dB	Area LXWXH
Banaei, M., Yazdanfar, A., Hatami, J., & Gramann, K.	2017	7	8	15[a]	28.6	2.6	3D Virtual HTC Vive (head mounted) Unity Game software	NR	NR	NR	NR	NR
Rodríguez, A., Rey, B., & Alcañiz, M.	2011	5	5	10	26.8	1.751	3D Virtual CAVE-like (Stereoscopic)	NR	NR	NR	NR	NR
Shemesh, A., Talmon, R., Karp, O., Amir, I. et al.	2017	NR	NR	42	NR	NR	3D Virtual CAVE VizTech XL software	NR	NR	NR	Soundless[a]	12X12X6-8M
Tsunetsugu, Y., Miyazaki, Y., & Sato, H.	2005	15	0	15	NR	NR	Physical room	40 lx	21-23 °C	50–60% RH	NR	13M2
Vartanian, O., Navarrete, G., Chatterjee, A., Fich, LB. et al	2013	6	12	18	23.39	4.49	2D image in fMRI Signa Excite HD	NR	NR	NR	NR	NR
Vecchiato, G., Jelic, A., Tieri, G., Maglione, A. et al	2015a, b	7	5	12	26.8	2.4	3D Virtual CAVE using 3DS Max 2011 software	NR	NR	NR	NR	3 × 3 × 2.5M
Zhang, X., Lian, Z., & Wu, Y.	2017	10	10	10	~26	NR	Physical room	500 lx	22-24 °C	30–40% RH	NR	3.8X3.2 × 2.8M

NR = Not reported.
[a] **Data from two participants were removed from the final reported study due to errors in data collection.**4.2. Characteristics of the studies.

standard and generic, and some which were highly specific. Two studies (Shemesh et al., 2017; Tsunetsugu et al., 2005) did not disclose any criteria for the selection of participants. Normal or corrected-to-normal vision was stipulated for participants in four studies (Banaei et al., 2017; Rodríguez et al., 2011; Vartanian et al., 2015; Vartanian et al., 2013; Vecchiato, Tieri, et al., 2015b), and self-evaluated right handedness was required in two studies (Banaei et al., 2017; Vartanian et al., 2013, 2015). Participants in one study were described as 'healthy' without further clarification (Banaei et al., 2017), while 'healthy' was defined in one study via a list of exclusions: cardiovascular disease, skin disease, blindness, rhinitis, women in their menstrual period or unfamiliar with how to use a computer (X. Zhang et al., 2017). In contrast, two other studies (Vecchiato, Tieri, et al., 2015b), required only that participants have no previous experience/exposure to using virtual reality.

Only one study (X. Zhang et al., 2017) reported using statistical analysis (G*Power) to determine the required number of participants for statistical validity. This study used a within-subject design with paired t-tests to compare the effects. It was unclear how the sample size was calculated for the remainder of studies in this review. Across the seven studies, the mean number of participants was 18.86 with a standard deviation of 10.75. Although with small samples it is important to report effect size or correlation coefficients alongside p values, only one study (Vartanian et al., 2013, 2015) reported p value and z scores. Two EEG studies (Banaei et al., 2017; Vecchiato, Tieri, et al., 2015b) reported p values and correlation coefficients, while another (Shemesh et al., 2017) did not report inferential statistics for the EEG results. The remaining three studies only reported p values (Rodríguez et al., 2011; Tsunetsugu et al., 2005; X.; Zhang et al., 2017).

4.1.2. Setting (controlled experimental conditions)

The physical settings of the included papers comprised four studies of virtually experienced interior built-environments (Cave Automatic Virtual Environment or virtual reality headset) and two of physically experienced interior-built environments. One study was performed in a Magnetic Resonance Imaging (MRI) room using 2D images of built environments. In the MRI scanning environment, the participant lies still inside the bore and is presented with visual stimuli via a mirror above their eyes reflecting a screen projected from the end of the bore. Although the two papers resulting from this study did not report any data on the IEQ variables (lighting, humidity, temperature etc) of the environment, we would expect that the room where the study was conducted would achieve strict standards for medical/clinical environmental control.

Included studies focused on specific design elements such as geometry (2D) and form (3D), materiality and texture, style and context of interior furnishings, and the ceiling height/sense of enclosure of the space. Table 1 lists the IEQ variables in the environments of each study. Only two of the articles reviewed reported the lighting, temperature and humidity levels within the space. Both of these were experiments using a physical 'real' environment. It remains unclear if studies using headset or surround virtual reality were carefully monitoring and controlling these comfort parameters.

4.1.3. Intervention/s (variables being tested for)

4.1.3.1. Form and geometry. Three studies investigated the impact of form and geometry in virtual environments (two using EEG and one using fMRI. In (Banaei et al., 2017), participants were instructed to move through virtual environments to perceive room form from different perspectives. The self-reported results demonstrated that rooms with more linear geometries resulted in lower pleasure and arousal scores from participants (who had no former design experience) while rooms with curvature resulted in higher scores in these two domains. This finding is not unusual, with preference for curvature identified in neuroaesthetics studies involving objects (Gómez-Puerto, Munar, & Nadal, 2016). EEG data were analysed using Independent

Component Analysis (ICA) and Fast Fourier Transform (FFT), with dipole modelling based on MNI coordinates. Participants showed pronounced activity in the anterior cingulate cortex (ACC) for rooms self-evaluated as higher for pleasure and arousal, reflecting the subjective results. Activation was also seen in posterior cingulate cortex and occipital lobe during the perception of rooms as the participants moved through the spaces. The second study by Vartanian et al. (2013), which used fMRI, investigated the effect of rectilinear and curvilinear spaces that were either open or enclosed with high or low ceilings (total of 8 conditions). In the judgement of 'beauty', statistical parametric mapping demonstrated that the curvilinear conditions exclusively activated the ACC. Parametric analyses to investigate the covariation of brain activity for beauty and pleasantness was performed using first order polynomial expansion. For beauty, the frontopolar cortex (FPC), superior frontal gyrus (SFG), globus pallidus (GP), precuneus (PN), parahippocampus (PH), and middle occipital gyrus (MOG) were shown to be activated. The 'pleasantness' rating also activated the precuneus, as well as the middle frontal gyrus (MFG) and anterior cingulate cortex (ACC). Shemesh et al. (2017) used manifold learning techniques to analyse the EEG data, a technique not seen elsewhere in the literature reviewed. In this study, results confirmed data analysis could distinguish spaces, with brain activity in the first 2 s of exposure the most pronounced. The authors did not report on or provide an analysis of the effect seen in different interventions. To analyse the data obtained from the EEG, a single channel was used from the left parietal region (P7), which was compared against output from a right occipital electrode (O2). From these studies, whether movement is involved or not, we can see that curvature of objects or built environment activates the ACC, directly linked to the salience and reward properties of visual stimuli.

4.1.3.2. Furnishing style and context. Two studies explored the impact of the style of furnishings in a room using EEG as an objective measure. A description of furnishings in a bedroom context, whether 'empty', 'modern' or 'cutting-edge' was used in Vecchiato, Jelic, et al. (2015a) and Vecchiato, Tieri, et al. (2015b), in contrast to 'realistic' or 'materialistic' residential spaces, and a high-rise 'work' office in (Rodríguez et al., 2011). Vecchiato, Jelic, et al. (2015a) and Vecchiato, Tieri, et al. (2015b) used Independent Component Analysis with only artefact free trials considered for analysis. Power Spectral Density was calculated using theta and alpha/mu bands through time frequency analysis and topographic statistical maps. For interiors with high self-reported presence ratings, mass univariate analysis showed larger theta power across frontal and left temporal sites. Temporary alpha and mu band activations were observed across the frontal and central sites; however, these were not sustained. High comfort ratings were associated with increased theta activity across the frontal midline and significant desynchronization across the left central and frontal mu band. Overall, the authors concluded that the perception of pleasant interiors activated visuospatial processing regions in the fronto-parietal network, showing involvement of motor and cognitive processes during the evaluation of spaces.

In contrast, Rodríguez et al. (2011) conducted a pilot study with 10 volunteers. A difference in presence levels was found in stereoscopic versus non-stereoscopic environments, however this was only measured through a questionnaire. In this study, the choice for interior environments lacked rigour, with some variables presenting potential confounding factors e.g., 'office' view from a great height), and the contextual clues of the interiors evoking participant connotations (bedroom, workplace). The authors concluded that the study demonstrated higher reported presence levels with stereoscopic vision. Overall, these studies reveal little insight due to the spatial clues and affordances associated with the complex and contrasting visual stimuli presented.

4.1.3.3. Materiality and texture (wood). In X. Zhang et al. (2017), a variety of physiological indicators were able to illustrate significant differences between wooden interior settings: electrocardiography, blood pressure, electro-dermal activity, oxyhemoglobin saturation and near distance vision. Blood pressure, oxyhemoglobin saturation and skin conductance resonance were lower during exposure to three wooden room conditions, indicating that participants in these conditions were showing less signs of stress and tension. Near distance of the eye was also improved for participants with normal or myopic vision in the wooden room exposures, where task performance improved when compared to the control (non-wood) room. The second study investigating materiality and texture used wood panelling as the intervention. Tsunetsugu et al. (2005) found participants were unable to report difference between the two room conditions with varying wood details. However, autonomic nervous activity (pulse rate, blood pressure and regional cerebral blood flow) indicated a change in state, showing that self-evaluations were not as sensitive as physiological indices. Both blood pressure and pulse rate were elevated in the 'designed' room and regional cerebral blood flow was increased in both conditions. Participants were 'calmer' in the 'standard' room based on the physiological data obtained. This effect may have been due to sense of familiarity with a common stimulus. The experimental approach enabled a clear indication across both studies that wood as a materiality activated an ANS response which was not consciously identified through self-report with participants.

4.1.3.4. Height and enclosure. One study (Vartanian et al., 2013, 2015) investigated the effect of height and sense of enclosure through the use of 2D stimuli in an fMRI. Results were divided into behavioural (participant choice from approach-avoidance and beautiful-not beautiful decisions) and neural impacts (through analysing fMRI results with statistical parametric mapping). On the beauty judgement run for the high – low ceiling contrast, the left precuneus and left middle frontal gyrus were activated. During the beauty run in the open – enclosed contrast, the left middle temporal gyrus and right superior temporal gyrus were activated. No significant results were reported for high – low ceiling on the approach – avoidance run. The open – enclosed contrast revealed activity in the anterior cingulate cortex. The authors concluded that high ceilings and curvilinear spaces were judged as more beautiful, activating structures involved in visuospatial exploration. Enclosed rooms activated the anterior midcingulate cortex with higher exit decision. They concluded that the reduced visual and locomotive permeability (enclosed, low ceilings) elicits an emotional reaction to make an exit decision.

4.1.4. Control/comparator

The studies in this review controlled their experimental design by exposing participants to one of each of the environmental conditions in a randomised order. Only one showed clear differentiation within their population groups. As the split sample was to question if training in architecture changed participants perceptions/experiences of the built environment (Shemesh et al., 2017), half of the participants had previous training in architectural studies. Other studies included in the full text review did not discern between participants as a control factor.

A clearly distinguishable built environment exposure 'control' was used in three studies. These included studies investigating the effect of: form clusters by comparing a 'simple cubic room without significant form features' against 17 alternative room structures with different form (Banaei et al., 2017); furnishing style in a bedroom context by comparing to an 'empty room' (devoid of furnishings or evidence of inhabitancy) against 'modern' and 'cutting edge' furnished environments (Vecchiato, Tieri, et al. (2015b)); the effect of timber construction and panelling in office environments by comparing a physical (real) room constructed from steel and concrete, painted 100% white against three timber constructed rooms with varying percentages of light and dark wood panelling (X. Zhang et al., 2017); and another similar study on the effect of timber panelling with a 'standard' type of living room available to buy as the control with timber confined to the floorboards compared to a 'designed' room with wooden beams and columns (Tsunetsugu et al., 2005).

The remaining three studies did not clearly discern a control within their experimental design. These studies instead showed the differences between groups; investigating the effect of: geometry by comparing a square space, round space, sharp space and curvy space (Shemesh et al., 2017); enclosure by comparing an open high ceiling space, enclosed high ceiling space, open low ceiling space and enclosed low ceiling space (Vartanian et al., 2013, 2015); and furnishing typologies by comparing a 'realistic', 'materialistic' and 'office' virtual environment (Rodríguez et al., 2011).

4.1.5. Outcomes

EEG, used in three studies, was the most common output used for measuring objective neurophysiological response. Two studies used wet electrode systems (EASYCAP and BEMicro, EB Neuro), while one study used the dry electrode EMOTIV system. The number of electrodes ranged from 16 to 128. Sampling rate and band pass filter data was different across studies, indicating the diversity of protocols for collecting neurophysiological data. Two studies using EEG reported impedance was kept below 15 kΩ (Banaei et al., 2017) and 10 kΩ (Vecchiato, Tieri, et al. (2015b)). Table 2 shows the diversity in devices/technology, procedures and data extraction techniques (see Table 3).

Other forms of CNS data collection included fMRI (3 T MR, 8 Channel using SPM8) and fNIRS (NIRO-300). PNS measures included BP (FinaPres and TKBP-H01) and one study which combined ECG, SpO2 & SCR (PCG and PowerLab). As only single studies used each technique, results cannot be compared.

A variety of self-reported measures were used across the array of study designs. These included point scales (9 and 13 point), Profile of Moods Scale (POMS), Slater-Usoh-Steed (SUS) and Sanchez-Vives & Slater questionnaires and the Self-Assessment Manikin (SAM). Dimensions explored in these measures included experience, arousal, dominance, valence, familiarity, novelty, comfort, pleasantness and presence. Data was collected post-test (exposure) in five of the seven studies, while one study asked participants to use approach/avoidance decisions during exposure. Additionally, one study used a virtual Stroop test to measure attention and another required each participant to complete a written task during exposure (later evaluated for 'quality)'. These were given through the virtual environment (projected) and verbally.

4.2. Risk of bias

It is important to consider how the methodologies of the studies reviewed are open to risk. Five types of risk that need attending to have been discussed following the Cochrane tool for assessing risk of bias (Higgins JPT et al., 2017).

5. Discussion

This review investigated if studies examining visual properties of interior built-environments have, using a combination of brain/body responses in conjunction with self-reported measures, been able to show an impact on human emotion.

Within the interventions tested, four considered categorical groups of visual properties emerged: (1) geometry (2D) and form (3D), (2) style (time period/aesthetic) and context (cue to the space use) of interior furnishings, (3) materiality and texture, and (4) height and enclosure of the space. Noticeably, no studies reported on the effect of colour, scale or proportion which should be examined in future studies.

Studies in this review showed that experience (through training or exposure) effects emotion state. In Banaei et al. (2017), lower pleasure and arousal was found in conditions with more linear geometries, and

Table 2
Details of the parameters and conditions from the three studies using EEG to record correlates of neurophysiological response. This included the brand of device, cap and analysis software, the type of system, number of electrodes and channels, sampling rate, band pass filter and impedance. As some studies encouraged participants to move freely this has also been recorded as it may have affected the data collected.

	EEG parameters and conditions used					
	Brand & software	Wet/Dry System	No. of electrode/channels	Sampling rate & filtering	Impedance	Movement allowed?
Banaei, M., Yazdanfar, A., Hatami, J., & Gramann, K. (2017)	EASYCAP with EEGLAB toolbox	Wet	128	1000 Hz hp = 0.016 Hz; lp = 250 Hz	< 15 kΩ	No
Shemesh, A., Talmon, R., Karp, O., Amir, I. et al. (2017)	EMOTIV	Dry	16/14	NR	NR	Yes
Vecchiato, G., Jelic, A., Tieri, G., Maglione, A. et al. (2015)	BEMicro, EBNeuro wth EEGLAB	Wet	19/24	256 Hz hp = 0.5 Hz; lp = 45 Hz	< 10 kΩ	No

Table 3
A list of the types of bias encountered across the reviewed studies and what steps were taken by the authors to reduce the risk.

Allocation	Six of the seven studies did not disclose how intervention allocation was determined; leading to unclear risk. X. Zhang et al. (2017) documented that sequence generation was determined by a Latin Square Design to ensure the order of exposure did not affect the results observed.
Blinding	All studies sampled participants individually, thus reducing the likelihood participants were aware of a classification grouping (such as 'expert' for participants of a design background). It is unclear whether participants were blind to the experimental design purpose as exposure to the built environment is highly visible. It is also unclear whether the personnel carrying out the experiments were blinded to the categorisation of participants and orders of exposure. All studies included exposures to control and experimental conditions. In (Vartanian et al., 2013, 2015) the enclosed fMRI environment may have reduced the risk of performance and detection bias by personnel dependent on the level of automation in the experimental procedure.
Incomplete outcome data	Two studies report incomplete data, flagging potential attrition bias. Both these studies explain participants removal as due to technical difficulties with objective data collection and excessive noise in the analyse of the data.
Selective reporting	Two studies showed unclear risk of reporting bias as only significant result was reported in the papers. Six papers report non-significant findings alongside significant findings; reducing the risk selective reporting has occurred.
Other potential sources of bias	A key contamination concern is that the comfort qualities of the experienced built environments are not being reported. As these qualities, referred to as Indoor Environmental Quality (IEQ) variables, play a significant role in the experience of environments, their variation have high risk of biasing the results when not monitored and stabilised. X. Zhang et al. (2017) is the only study in the review reporting physical environmental parameters of temperature, relative humidity and luminance levels. We can reasonably assume a level of control in one study (Vartanian et al., 2013, 2015) where the environment was stabilised due to the clinical fMRI environment where the study took place. Uncontrolled IEQ measures pose the greatest risk in biasing the effect reported in studies

Shemesh et al. (2017) showed participants with design training showed deviation to non-design trained participants. Although it is difficult to make broad claims, it could be suggested that familiarity with design characteristics may not be 'enriching' to stimulate the brain. In other words, dependent on our experience, it is important that we actively seek out new dynamic spaces to ensure we regulate stimulation. This raises the question of whether novel environments with uncommon design characteristics are important for 'enrichment'? In particular, should designers use uncommon and unique design features to simulate brain activity and does this enhance positive emotional states?

Critically, X. Zhang et al. (2017) and Tsunetsugu et al. (2005) demonstrated that ANS response to materiality (wood) occurs without conscious perception of emotion change in the participant. This demonstrates that current practice should not rely on occupant self-reported evaluation of buildings alone.

Methodologically, the results highlighted that: (1) limited studies have been conducted in this field; (2) studies have small sample sizes with little diversity in participants and; (3) there is a broad array of methodological and reporting procedures being used. In conjunction with these limitations, no studies reported effect size, demonstrating that a meta-analysis is not yet possible for this area of research.

Four chief limitations are observed across the field:

1. While all papers reported experimental approaches verifying that exposure to the built environment impacts emotional states, none used the same strategy for measuring or reporting this effect. Due to the range of different approaches being used, ability is limited to synthesise and cross validate through replication of the findings.
2. There was significant underpowering across the studies, with an average sample size of 19 participants and a very small variation in the age group sampled. With a young pool of participants, it is not clear whether this is due to age related experimental intentions, or simply because the participants were all taken from tertiary institutions (which might indicate a level of training/education higher than the average population).
3. There was a lack of consistency in data analysis procedures used across the studies. With the use of multiple statistical analyses techniques, there is a risk for reproducibility; although this is not unusual in the cognitive neurosciences. This heavy reliance on statistical measures to separate multivariate data suggests the experimental designs employed required further consideration to produce clearer results.
4. Similarly, a range of data representation methods were used; suggesting uncertainty in the field for the best techniques to represent data. In order to aid communication, plotted data would enable a more representative and transparent visual than bar graphs. Due to the limited sample sizes, p values should be presented alongside effect size or correlation coefficient values, and the representation of box and whisker plots should use confidence intervals instead of standard deviations for error bars.

The methodology of future studies must carefully consider how the use of technology to simulate a controlled built environment interacts with objective measuring systems. The key cortical surface areas to monitor for activation from the perception of visual stimuli will be in the occipital (receiving visual input), temporal (recognising and identifying objects) and parietal (understanding object movement and location) regions that are involved in the process of perception. We would also expect activation of the prefrontal cortex during the interpretation of stimuli to emotional state. Considering the locations of surface level cortical areas involved in this complex process, it is important that studies using head mounted VR are not impeding EEG channels over regions of the scalp where brain activity is expected. As a result, we suggest that a CAVE rather than a head mounted VR device will provide a more robust experimental design.

Investigations using fMRI and sophisticated modelling in EEG can provide a deeper insight into the neural pathways, networks and structures activated during visual perception and emotional response. From the areas activated in the included studies, this would likely include cortical/subcortical networks involved in emotion and regulation processes. In particular the ACC, which has extensive prefrontal and limbic connectivity, was identified across four of the studies in both fMRI and EEG data. As the ACC is involved with reward properties and the salience of visual properties, this is not of surprise and reinforces that areas involved with emotion processing are activated when appraising features of the built environment.

Other physiological tools such as GSR, HR and BP are helpful for determining if the body is reacting to a stimulus. These measures require precise and measured experimental conditions to ensure the reaction is to the stimulus being tested rather than to a confounding variable in the setup (such as temperature, ambient noise, associated memory etc). Although these measures provide information that the body is recognising and responding to a stimulus, they are not useful as lone measures for detecting why neural activation is occurring and where it is originating. Therefore, these tools are suited to confirm a reaction is occurring, while fMRI or EEG can show what CNS activity is occurring. Combining these measures with a form of self-report is critical to further identify if the participant is consciously aware of a change in emotional state to stimulus.

6. Conclusion

Currently there is no standard, accepted, cross-validated protocol or methodology for evaluating how design of built environments affects neurophysiological correlates of emotion in humans. This has resulted in an array of techniques and approaches for conducting the research, making a meta-analysis of effect across studies a non-viable option at this point in time. At present there is a lack of comprehensive studies using and reporting controls for environmental comfort elements to determine whether design characteristics affect neurophysiological responses. In order to progress the field, a rigorous protocol that reports the comfort parameters of the controlled experimental environment is needed before we establish the effect of visual design variables on emotion in interior built environments.

The body of evidence collected does not provide robust evidence for the neurophysiological effect in interior spaces to different visual properties of the built environment. However, the field does suggest that emotional state is affected by visual properties that can be objectively measured, and which result in a range of neural and physiological activity. It is also important to note that brain and body activity in response to design characteristics can occur without conscious perception. Knowledge and measurability of these impacts may give rise to a new standard for evaluating built environments. This review highlighted that more work is needed with greater rigour in experimental design and analysis. Although the evidence summarised in this review is only from seven studies, key methodological limitations are observed across them: not reporting environmental IEQ parameters; inconsistent reporting of participant characteristics; not disclosing the method and rationale for calculating sample size; presenting p values without effect size or correlation coefficients; and the use of different techniques (type of measure, type of system), protocols (impedance, sampling rate, filters) and programs (interfaces for data output and algorithms/transformations applied) for decoding objective data.

It is important to consider why we make subjective decisions and opinions about built environments and whether neurophysiological processes are affecting our mental states and self-reported feelings towards spaces. In order for built environment practitioners to have a clear understanding of the impacts of the visual characteristics (informed by design decisions) of interior built environments on emotion, it is critical that standard practice is established for measuring and evaluating the emotional impact of the built environment, and that studies follow guidelines in reporting the parameters of the experimental design for transparency and for reproducibility. Through developing a reproducible and cross-validated technique that can be used alongside subjective post-occupancy tools in evaluating buildings, new formal and informal standards for the design of our environments across sectors (education, healthcare, commercial, residential) and countries could transform how industry and government value the design of interior built environments. If the impact of design characteristics can be understood on a neurophysiological level, this opens the door to understanding if we can support mental health and wellbeing (in both healthy and clinical populations) non-invasively through environmental exposure as a recognised form of therapy.

Declarations of interest

Isabella Bower is supported by funding from the Academy of Neuroscience for Architecture (ANFA) and Creative Futures Pty Ltd. Peter G. Enticott is supported by a Future Fellowship from the Australian Research Council (ARC) (FT160100077).

Appendices

Appendix A
Search strings and databases used. These results were last updated on 3rd January 2019.Table Appendix A

Engine	Search String	Results
CINAHL	(Interior Design*) AND (Affect OR Emotion*)	97
EMBASE	('built environment'/exp OR ′built environment' OR interior OR spatial) AND ('affective response' OR ′emotion* response')	55
MEDLINE	(Built Environment*) AND (Affect OR Emotion*) Publication: 20010101–20181231 English Language	426
PsycINFO	(Built Environment OR Interior) AND (Affect* OR Emotion*) Publication Year: 2000–2019 Language: English	931
Science Direct	(Interior Design AND Physical AND Built Environment) AND (Emotion) Publication Year: 2000–2019	789
Scopus	TITLE-ABS-KEY (*interior* AND *design* AND *emotion*) AND PUBYEAR > *1999*	98
Web of Science	TOPIC: (((Interior Design AND Architect* AND Buil*) AND (Affect OR Emotion*))) Timespan: 2000–2019. Databases: WOS, MEDLINE. Search language = English	96

References

AIWH (2018). *Mental health services in Australia, summary of mental health services in Australia - Australian institute of health and welfare.* Retrieved from https://www.aihw.gov.au/reports/mental-health-services/mental-health-services-in-australia/report-contents/summary.

Altman, I., & Wohlwill, J. F. (1976). *Human behavior and environment : Advances in theory and research.* New York: Plenum Press 1976.

Arundel, R., & Ronald, R. (2017). The role of urban form in sustainability of community: The case of Amsterdam. *Environment and Planning B: Urban Analytics and City Science, 44*(1), 33–53.

Banaei, M., Yazdanfar, A., Hatami, J., & Gramann, K. (2017). Walking through architectural spaces: The impact of interior forms on human brain dynamics. *Frontiers in Human Neuroscience, 11*. https://doi.org/10.3389/fnhum.2017.00477.

Barker, R. G. (1978). *Habitats, environments, and human behavior* (1st ed.). San Francisco: Jossey-Bass 1978.

Bechtel, R. B. (1977). *Enclosing behavior: Dowden.* Hutchinson & Ross.

van den Bosch, M., & Bird, W. (2018). *Oxford textbook of nature and public health : The role of nature in improving the health of a population* (1st ed.). Oxford: Oxford University Press 2018.

Chiamulera, C., Ferrandi, E., Benvegnù, G., Ferraro, S., Tommasi, F., Maris, B., et al. (2017). Virtual reality for neuroarchitecture: Cue reactivity in built spaces. *Frontiers in Psychology, 8*(185), https://doi.org/10.3389/fpsyg.2017.00185.

Clemenson, G. D., Deng, W., & Gage, F. H. (2015). Environmental enrichment and neurogenesis: From mice to humans. *Current Opinion in Behavioral Sciences, 4,* 56–62. https://doi.org/10.1016/j.cobeha.2015.02.005.

Dazkir, S. S., & Read, M. A. (2012). Furniture forms and their influence on our emotional responses toward interior environments. *Environment and Behavior, 44*(5), 722–732. https://doi.org/10.1177/0013916511402063.

Dewing, J. (2009). Caring for people with dementia: Noise and light. *Nursing Older People, 21*(5), 34–38.

Dinis, S., Duarte, E., Noriega, P., Teixeira, L., Vilar, E., & Rebelo, F. (2013). *Evaluating emotional responses to the interior design of a hospital room: A study using virtual reality. Paper presented at the design, user experience, and usability. User experience in novel technological environments, berlin, heidelberg.* 2013//.

Eberhard, J. P. (2009). Applying neuroscience to architecture. *Neuron, 62*(6), 753–756. https://doi.org/10.1016/j.neuron.2009.06.001.

Edelstein, E. A., Gramann, K., Schulze, J., Shamlo, N. B., van Erp, E., Vankov, A., et al. (2008). Neural responses during navigation in the virtual aided design laboratory: Brain dynamics of orientation in architecturally ambiguous space. *Movement and Orientation in Built Environments: Evaluating Design Rationale and User Cognition, 35,* 35–41.

Edelstein, E., & Macagno, E. (2012). Form follows function: Bridging neuroscience and architecture. In S. T. Rassia, & P. M. Pardalos (Eds.). *Sustainable environmental design in architecture: Impacts on health* (pp. 27–41). New York, NY: Springer New York.

Elbaiuomy, E., Hegazy, I., & Sheta, S. (2018). The impact of architectural spaces' geometric forms and construction materials on the users' brainwaves and consciousness status. *International Journal of Low Carbon Technologies, 13*(1), 43–51. https://doi.org/10.1093/ijlct/ctx018.

Evans, G. W., & McCoy, J. M. (1998). When buildings don't work: The role of architecture in human health. *Journal of Environmental Psychology, 18*(1), 85–94. https://doi.org/10.1006/jevp.1998.0089.

Evans, G. W., Schroeder, A., & Lepore, S. J. (1996). The role of interior design elements in human responses to crowding. *Journal of Personality and Social Psychology, 1,* 41.

Ferguson, K. T., & Evans, G. W. (2018). *The built environment and mental health reference*

Module in earth Systems and environmental sciences. Elsevier.

Fich, L. B., Jönsson, P., Kirkegaard, P. H., Wallergård, M., Garde, A. H., & Hansen, Å. (2014). Can architectural design alter the physiological reaction to psychosocial stress? A virtual TSST experiment. *Physiology & Behavior, 135*, 91–97. https://doi.org/10.1016/j.physbeh.2014.05.034.

Fox, C., Merali, Z., & Harrison, C. (2006). Therapeutic and protective effect of environmental enrichment against psychogenic and neurogenic stress. *Behavioural Brain Research, 175*(1), 1–8. https://doi.org/10.1016/j.bbr.2006.08.016.

Francis, J., Giles-Corti, B., Wood, L., & Knuiman, M. (2012). Creating sense of community: The role of public space. *Journal of Environmental Psychology, 32*(4), 401–409.

Fried, M. (1982). Residential attachment: Sources of residential and community satisfaction. *Journal of Social Issues, 38*(3), 107–119.

Gómez-Puerto, G., Munar, E., & Nadal, M. (2016). Preference for curvature: A historical and conceptual framework. *Frontiers in Human Neuroscience, 9*(712), https://doi.org/10.3389/fnhum.2015.00712.

Higgins JPT, A. D., & Sterne, J. A. C. (2017). Chapter 8: Assessing risk of bias in included studies.Cochrane Handbook for systematic reviews of interventions version 5.2.0. In C. R. Higgins JPT, J. Chandler, & M. S. Cumpston (Eds.). *Cochrane*. Retrieved from www.training.cochrane.org/handbook.

Higgins, J., & Green, S. (2011). *Cochrane Handbook for systematic reviews of interventions.* 2018.

Kiecolt-Glaser, J. K., McGuire, L., Robles, T. F., & Glaser, R. (2002). EMOTIONS, morbidity, and mortality: New perspectives from psychoneuroimmunology. *Annual Review of Psychology, 53*(1), 83. https://doi.org/10.1146/annurev.psych.53.100901.135217.

Kim, M., Chong, S. C., Chun, C., & Choi, Y. (2017). Effect of thermal sensation on emotional responses as measured through brain waves. *Building and Environment, 118*, 32–39. https://doi.org/10.1016/j.buildenv.2017.03.023.

Kirk, U., Skov, M., Christensen, M. S., & Nygaard, N. (2009). Brain correlates of aesthetic expertise: A parametric fMRI study. *Brain and Cognition, 69*(2), 306–315. https://doi.org/10.1016/j.bandc.2008.08.004.

Klepeis, N. E., Nelson, W. C., Ott, W. R., Robinson, J. P., Tsang, A. M., Switzer, P., et al. (2001). The national human activity pattern survey (NHAPS): A resource for assessing exposure to environmental pollutants. *Journal of Exposure Analysis and Environmental Epidemiology, 11*, 231. https://doi.org/10.1038/sj.jea.7500165.

Küller, R., Ballal, S., Laike, T., Mikellides, B., & Tonello, G. (2006). The impact of light and colour on psychological mood: A cross-cultural study of indoor work environments. *Ergonomics, 49*(14), 1496–1507. https://doi.org/10.1080/00140130600858142.

Lazarus, R. S. (1991). *Emotion and adaptation.* Oxford University Press on Demand.

Lee, Y., & Hsieh, S. (2014). *Classifying different emotional states by means of EEG-based functional connectivity patterns, Vol. 9*.

Liddell, B. J., Brown, K. J., Kemp, A. H., Barton, M. J., Das, P., Peduto, A., et al. (2005). A direct brainstem–amygdala–cortical 'alarm' system for subliminal signals of fear. *NeuroImage, 24*(1), 235–243. https://doi.org/10.1016/j.neuroimage.2004.08.016.

Mavros, P., Austwick, M. Z., & Smith, A. H. (2016). Geo-EEG: Towards the use of EEG in the study of urban behaviour. *Applied Spatial Analysis and Policy, 9*(2), 191–212. https://doi.org/10.1007/s12061-015-9181-z.

Ma, K. W., Wong, H. M., & Mak, C. M. (2018). A systematic review of human perceptual dimensions of sound: Meta-analysis of semantic differential method applications to indoor and outdoor sounds. *Building and Environment, 133*, 123–150. https://doi.org/10.1016/j.buildenv.2018.02.021.

McDonald, M. W., Hayward, K. S., Rosbergen, I. C. M., Jeffers, M. S., & Corbett, D. (2018). Is environmental enrichment ready for clinical application in human post-stroke rehabilitation? *Frontiers in Behavioral Neuroscience, 12*. https://doi.org/10.3389/fnbeh.2018.00135 135-135.

Nanda, U., Ghamari, H., Pati, D., & Bajema, R. (2013). Lessons from neuroscience: Form follows function, emotions follow form. *Intelligent Buildings International, 5*(SUPPL1), 61–78. https://doi.org/10.1080/17508975.2013.807767.

Nithianantharajah, J., & Hannan, A. (2006). Enriched environments, experience-dependent plasticity and disorders of the nervous system. *Nature Reviews Neuroscience, 9*, 697.

Öhman, A., Flykt, A., & Lundqvist, D. (2002). Evolutionary perspectives, psychophysiological data, and neuropsychological mechanisms. *Cognitive neuroscience of emotion,* 296.

Papale, P., Chiesi, L., Rampinini, A. C., Pietrini, P., & Ricciardi, E. (2016). When neuroscience 'touches' architecture: From hapticity to a supramodal functioning of the human brain. *Frontiers in Psychology, 7*, 866. https://doi.org/10.3389/fpsyg.2016.00866.

Parkinson, T., & De Dear, R. (2016). Thermal pleasure in built environments: Spatial alliesthesia from contact heating. *Building Research & Information, 44*(3), 248–262. https://doi.org/10.1080/09613218.2015.1082334.

Pati, D., O'Boyle, M., Hou, J., Nanda, U., & Ghamari, H. (2016). Can hospital form trigger fear response? *HERD, 9*(3), 162–175. https://doi.org/10.1177/1937586715624210.

Radwan, A., & Ergan, S. (2017). *Quantifying human experience in interior architectural spaces*.

Rodríguez, A., Rey, B., & Alcañiz, M. (2011). Immersive virtual environments for emotional engineering: Description and preliminary results. *Annual Review of CyberTherapy and Telemedicine, 9*, 161–164.

Roe, J., Aspinall, P., Mavros, P., & Coyne, R. (2013). *Engaging the brain: The impact of natural versus urban scenes using novel EEG methods in an experimental setting, Vol. 1*.

Roessler, K. K. (2012). Healthy Architecture! Can environments evoke emotional responses? *Global Journal of Health Science, 4*(4), 83–89.

Sampson, R. J., Morenoff, J. D., & Gannon-Rowley, T. (2002). Assessing" neighborhood effects": Social processes and new directions in research. *Annual Review of Sociology,* 443–478.

Schoggen, P., Barker, R. G., & Fox, K. A. (1989). *Behavior settings : A revision and extension of roger G. Barker's ecological psychology.* Stanford, Calif.: Stanford University Press 1989.

Sharma, G., Kaushal, Y., Chandra, S., Singh, V., Mittal, A. P., & Dutt, V. (2017). Influence of landmarks on wayfinding and brain connectivity in immersive virtual reality environment. *Frontiers in Psychology, 8*(1220), https://doi.org/10.3389/fpsyg.2017.01220.

Shemesh, A., Talmon, R., Karp, O., Amir, I., Bar, M., & Grobman, Y. J. (2017). Affective response to architecture – investigating human reaction to spaces with different geometry. *Architectural Science Review, 60*(2), 116–125. https://doi.org/10.1080/00038628.2016.1266597.

Skjaeveland, O., & Garling, T. (1997). Effects of interactional space on neighbouring. *Journal of Environmental Psychology, 17*(3), 181–198.

Steinmetz, J., & Posten, A.-C. (2017). Physical temperature affects response behavior. *Journal of Experimental Social Psychology, 70*, 294–300. https://doi.org/10.1016/j.jesp.2016.12.001.

Tsunetsugu, Y., Miyazaki, Y., & Sato, H. (2005). Visual effects of interior design in actual-size living rooms on physiological responses. *Building and Environment, 40*(10), 1341–1346. https://doi.org/10.1016/j.buildenv.2004.11.026.

Unger, D. G., & Wandersman, A. (1985). The importance of neighbors: The social, cognitive, and affective components of neighboring. *American Journal of Community Psychology, 13*(2), 139–169.

Van Praag, H., Kempermann, G., & Gage, F. (2000). Neural consequences of enviromental enrichment. *Nature Reviews Neuroscience, 1*(3), 191.

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. *Journal of Environmental Psychology, 41*, 10–18. https://doi.org/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. *Proceedings of the National Academy of Sciences, 110*(Supplement 2), 10446–10453. https://doi.org/10.1073/pnas.1301227110.

Vecchiato, G., Jelic, A., Tieri, G., Maglione, A. G., De Matteis, F., & Babiloni, F. (2015a). Neurophysiological correlates of embodiment and motivational factors during the perception of virtual architectural environments. *Cognitive Processing, 16*(1), 425–429. https://doi.org/10.1007/s10339-015-0725-6.

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

Zhang, X., Lian, Z., & Wu, Y. (2017). Human physiological responses to wooden indoor environment. *Physiology & Behavior, 174*, 27–34. https://doi.org/10.1016/j.physbeh.2017.02.043.

Zhang, L., Mike Chi, Y., Edelstein, E., Schulze, J., Gramann, K., Velasquez, A., et al. (2010). *Wireless physiological monitoring and ocular tracking: 3D calibration in a fully-immersive virtual health care environment, Vol. 2010*.