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REVIEW

The impact of the design of learning spaces on attention and memory from a neuroarchitectural approach: A systematic review

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Abstract Enriched environments in animal models have demonstrated that exposure to an optimal stimulus improves behavior, cognition, and genomics. However, the evidence base for the neurophysiological influence of human environment enrichment has not been extensively studied. This systematic review compiles indicators about the effect of built, indoor environments on the cognitive processes of memory and attention in humans. This work pursues two main objectives: (1) to define current knowledge and the methods that are useful and identify whether previously published studies indicate consistencies and (2) to report the approaches and strategies that can be used in evaluating cognitive processes affected by environment response. Results of this systematic review show that (1) form and geometry, (2) space distribution and context, (3) color and texture, (4) height, width, and enclosure, (5) transition and circulation, and (6) light, sound, and temperature have an impact on memory and/or attention, and they can be assessed objectively. Despite all the advances in this field, methodological limitations and a lack of cross-validated standard protocols are found. Therefore, future research is necessary to provide a deep insight into how human cognition can be heightened by the environment to which it is exposed.

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Contents

1. Introduction

As modern medicine has evolved into an evidence-based practice (Sackett, 1997), other disciplines, such as architecture, have developed along the same lines (Viets, 2009). This evolution is led by connecting physical environments and health outcomes using an evidence-based design (EBD) method (Steglitz et al., 2015). EBD has spread from healthcare buildings (Jamshidi et al., 2020) to other functional types of spaces, such as classrooms, which is one of the most studied environments at present (Oblinger and Lippincott, 2006; Lippman, 2000). In addition, learning spaces are essential in this field because cognitive ability can only be enhanced at an early age (Kremen et al., 2019). Nonetheless, general cognitive ability and specific cognitive performance must be distinguished at a given time (Plomin, 1999). The former may be relatively static, but the latter is highly environmentally dependent (Thompson et al., 2017). This environment dependence is precisely the main interest in this review.

The premise for studying learning spaces is that built environments affect cognitive processes, such as attention and memory (Anderson, 2000; Marchand et al., 2014). Memory and attention are the basis for cognition, and these cognitive systems stand out in this field as the main mechanisms involved in learning processes (Ritter et al., 2014). These studies are based mainly on learning processes, evidence, and academic results (Barrett et al., 2013, 2017; Byers et al., 2014; Weinstein, 1977).

The literature in this field traditionally includes studies that have been performed in either real-life classrooms or laboratories (Benmohamed et al., 2004; Patten and Michelle Newhart, 2018). However, both scenarios have limitations. First, studies conducted in real-life classrooms cannot control or isolate variables (Bovy, 1981; Polio, 1996). Second, much effort is needed to modify or build the possible variables in laboratory studies (Rizzo et al., 2000).

Another traditional limitation concerns the methodology used in all these studies regardless of the scenario. Thus, subjective methodologies, such as self-evaluated rating scales or questionnaires, have been used extensively in this field (Naismith et al., 2015). Subjective measurements are essential instruments for understanding the perception of experiences, but they alone are not enough to quantify, compare, and explain this impact (Agnello et al., 2015). In addition, certain authors have argued that such assessments show variations in ethnicity and cultural groups in tests because of the language used (Öhman et al., 2000). Another problem is that the human body sometimes reacts to a stimulus before the input can be processed consciously (Eberhard, 2009; Nanda et al., 2013). Consequently, how the built environment and its design can affect perception has not been systematically defined (Akil et al., 2016; Stevens et al., 2019). This issue used to be studied from a one-discipline approach with no well-defined correlations.

However, many multidisciplinary research teams have recently emerged with support from new technological advances in a mature industry (Papale et al., 2016). This new multidisciplinary approach, called *neuroarchitecture* by the Academy of Neuroscience for Architecture (Sternberg and Wilson, 2006), combines neuroscience and architecture, even though these two fields do not have many features in common (Francis Mallgrave, 2009; Pallasmaa et al., 2013). Architects have traditionally relied on perception and instinct rather than the scientific and experimental methods on which neuroscience studies are based (Isabella Bower, 2019; Waldman et al., 2019). However, the latest advances in neuroscience can now explain how our perception of the world and how we explore it can affect our emotions, problem-solving ability, and cognition (Rizzo et al., 2009; Bower et al., 2019; Choo et al., 2017; Escera et al., 2002; Landau et al., 2007; Radwan and Ergan, 2017). One great advantage of these neuroscientific methods is, for example, that they allow the involuntary responses of the subjects to be measured (de Kort et al., 2003; Parsons et al., 2007). Moreover, the use of virtual reality (VR) combined with neuroscientific methods for neuronal, psychological, and physical outcome measurement in situ is a remarkable advancement in this field (Hu and Roberts, 2020; Higgins and Green, 2011). VR can solve the problem of controlling and isolating the design variables of built environments (Ansari and Coch, 2006). Thus, the convergence of literature about neuroscience and architecture in recent years has revealed a wide range of ideas and theories, giving an insight into this field (Karakas and Yildiz, 2020).

Despite all the advances in this field (Higuera-Trujillo et al., 2021; Karakas and Yildiz, 2020), a dearth of studies that systematically classify neuroscientific methods to analyze the impact of built environment design on cognitive processes is found. This systematic review has two main objectives. The first one is to outline the current landscape of recent research demonstrating the link between the design of learning spaces and specific cognitive processes, such as attention and memory. The second is to explore the tools and methodologies that can simulate and measure the impact of learning space design on cognitive processes.

Table 1 Search strings used. Results were updated on July 25, 2021.

Search String
(Cognition) AND (Neuro-architecture OR Architecture OR Neuroscience)
(Attention OR Memory) AND (Neuro-architecture OR Architecture OR Neuroscience) AND (Design variable)
(Attention OR Memory) AND (Neuro-architecture OR Architecture OR Neuroscience) AND (Learning space)
(Attention OR Memory) AND (Neuro-architecture)
(Attention OR Memory) AND (Design variables) AND (Learning space)

2. Material and methods

A systematic and rigorous methodology has been adopted in our research. The steps taken and their criteria are based on the principles described in the Cochrane Handbook (Cochrane, 2020). This section covers the data collection, inclusion criteria, and data synthesis.

2.1. Data collection

The data were collected by searching for the most common strings of words (see Table 1) that complied with the following criteria: studies reviewed by peers, written in English, and published in the last 20 years (from 2000 to 2020). This period includes the most remarkable work in this field because of technological developments and reflects recent enthusiasm for this interdisciplinary field. The Publish or Perish software (Harzing, 2020) was used for the search.

The final list of search strings was filtered for 6 months after examining several databases in the areas of architecture, social science, and neurosciences (Web of Science, PubMed, Google Scholar, Scopus, and Avery Index). After identification followed by screening, 164 documents focused on attention and memory were selected for examination.

2.2. Selection criteria

This systemic review includes any research or study that investigates the impact of built environment design variables. The selection criteria applied in this systematic review were chosen to ensure a rigorous and accurate revision of the impact of learning space design on attention and memory. Attention and memory were chosen because they are essential to achieving satisfactory academic performance in cognitive functions (Fenollar et al., 2007). Attention is a process of selecting and controlling processing information (Bargh, 1982), whereas memory is an active process in which information is retained at short, medium, or long term and gets updated (Nadel and Hardt, 2010). These functions affect learning in an interdependent way, and their relationship has been extensively studied (Chun and Turk-Browne, 2007; Lyon et al., 1996; Robinson, 1995; Williams, 1999).

The studies must fulfill several criteria to be selected for the review. First, they have to feature subjects' attention and memory exposed to controlled conditions of design variables (geometry, color, and light) in either a simulated or real-life built environment. Second, they have to describe a nervous system response and/or psychometric methods of self-reported perception state. In the latter instance, an extension of different methodologies using both objective and subjective measures was searched because of the limited literature available. The descriptors of central and/or autonomic nervous system responses used in the selected studies include electroencephalography (EEG) and functional magnetic resonance imaging (fMRI). Animal models were excluded from the present work because of the actual scientific evidence obtained from studies of human populations. Participants belong to healthy or clinical population groups. Although this review aims to seek out studies using random samples, the little literature found focuses on cohorts of participants of a similar age, background education, geographical location, and/or ethnic group.

2.3. Data synthesis

The first author of this review listed the title and abstract of the publications in order to select the studies whose entire text was to be evaluated. The entire process was supervised and checked by the other authors. Thirty-seven papers were eligible for a full-text revision. The first author independently performed data extraction using an adaptation of the Cochrane method (Cochrane, 2020) to compile information about the aim of the study, quotations, impact factor, materials and methods (participants, stimulus, method, and data analysis), results, and notes with additional information to consider. The authors analyzed the dataset individually. These procedures decreased the number of studies included in this review to 14.

The selection process (Fig. 1) used the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) method (Moher et al., 2009). The Cochrane risk-of-bias tool was used in this study to define the quality of the selected papers. The findings discuss the observations made after the bias study (Higgins et al., 2020).

The selection process eliminated two studies performed in real-life classrooms that only reported student—professor interaction: one is based on the class size method (Blatchford et al., 2011), and the other is based on the distribution of space and furniture (Cardellino et al., 2018). Another seven studies excluded were based on academic results instead of a specific cognitive process; one of them also focused on health parameters (Küller and Lindsten, 1992). Some authors assumed that an enhanced learning process or academic results are related to improved attention (Stojić et al., 2020) and cognitive processes. However, notable studies about the impact of classroom design on academic results or specific tasks have been excluded from this review because they fail to demonstrate the links to specific cognitive processes (Baek and Choi, 2002; Barrett et al., 2013, 2015, 2017; Byers et al., 2014; Tanner, 2009). The excluded research provides useful knowledge about the impact of classroom size or layout. Thus, this review focuses specifically on controlled cognitive processes. Other notable papers excluded are related to studies about emotional responses to geometry (Banaei et al., 2019; Shemesh et al., 2017), materiality (Tsunetsugu et al., 2002; Zhang et al., 2017), spatial distribution and context (Zou et al., 2019), and lighting (Castilla et al., 2018a; 2018b), among others. Although stress and emotion are influential, incorporating them into experimental procedures and conditions can modify brain function. Moreover, the magnitude of emotional response is not the objective of this review. However, the excluded studies include valid methodologies for determining the impact of environment design on the human experience of comfort, stress reduction (Ergan et al., 2019; Higuera-Trujillo et al., 2020; Pourbagher et al., 2020), and emotional perceptions (Shemesh et al., 2021; Tsunetsugu et al., 2002).

3. Results

After the thorough sorting of data, only 14 studies that met the inclusion criteria remained. The impact on cognitive processes, methods (recorded outcomes), materials (environment and experimental conditions), population, interventions (variables tested), control/comparator, and risk of bias of the selected studies were analyzed (see Table 2).

The selected studies were conducted from 2007 to 2021. Most of them were published in the last 6 years. This period reflects the recent boom in this type of interdisciplinary research.

3.1. Impact of built-environment design on cognitive processes

The selected studies show that interior design variables can impact the specific cognitive processes of attention and memory, the two mainstays of the learning process.

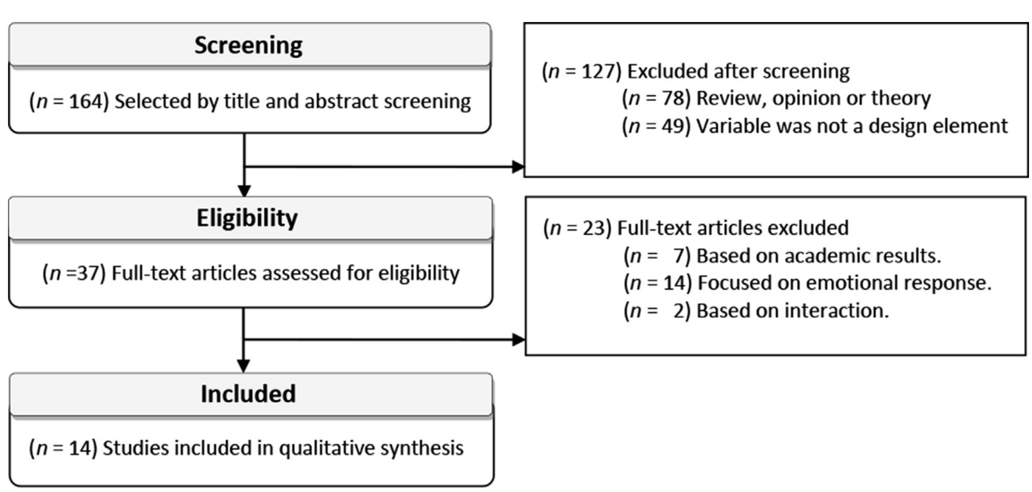

Fig. 1 Selection process using PRISMA.

Table 2 Classification of studies included in qualitative synthesis according to impact on cognitive processes (attention and memory), methods (psychometric and neurophysiological outcomes), and materials (environment and experimental conditions).

Studies	Attention	Memory	Subjective outcomes	Neurophysiological outcomes	Real environment	Simulation systems
Banaei et al., 2017	x		x	x		x
Djebbara et al., 2019	x		x	x	x	x
Duyan & Ünver, 2016	x		x		x	
Elbaiuomy et al., 2018	x	x		x		x
Llinares et al., 2021a	x	x	x	x		x
Llinares et al., 2021b	x	x	x	x		x
Marchand et al., 2014	x		x		x	
Meyers-Levy & Rui, 2007		x	x		x	
Min & Lee, 2020		x	x			x
Vartanian et al., 2015	x		x	x		x
Vecchiato et al., 2015a	x		x	x	x	
Vecchiato et al., 2015b	x		x	x	x	
Xiong et al., 2018	x	x	x		x	
Yang & Jeon, 2020		x	x		x	
	Cognitive processes		**Methods: Outcomes**		**Materials: environment**	

3.1.1. Attention

The cognitive processes involved in attention were analyzed in 11 of the selected studies through different procedures and techniques. In one study, attention was measured with a classic Stroop test (Stroop, 1935) at the end of each trial; the authors found that the attention of participants is comparable in different environments, but the potential differences in EEG were not explained (Banaei et al., 2017). Another psychological attention task similar to the auditory continuous performance test (Seidman et al., 1998) was used in two studies to quantify the number of errors and the reaction time to target stimuli (Llinares et al., 2021b, 2021a). Another test to evaluate the attention of participants is the Bourdon Attention Test (Grewel, 1953). It was used in one study of how classroom wall colors affect students' attention (Duyan and Ünver, 2016). In this experimentation, the test was repeated every five weeks, one for each color tested. The results showed that red walls negatively affect students' attention; in comparison, high scores were achieved with purple walls. Another study used an attention-oriented and number-searching test to assess the impact of the physical environment (i.e., temperature, noise, and illuminance) on the attention of persons using the learning space (Xiong et al., 2018). The results indicated that attention obtains the highest scores in a cool learning space, and a quiet environment (<50 dB) is necessary for better performance. Moreover, a well-lit environment can modulate attention processes regarding interaction with other physical parameters. In a completely different study, several environmental factors were controlled (light, sound, and temperature) simultaneously, and different psychometric methods were performed to analyze students' perceptions and learning (Marchand et al., 2014). This study conducted a built environment experience survey, which asked questions about attention during reading and listening tasks. The results showed that a learning space with a low ceiling may have a negative influence on adult learning during listening and other tasks. However, this study acknowledged that the lack of a thorough analysis of the measurements of attention and working memory is a limitation.

Apart from psychometric measurements, neurological techniques were also used in eight studies to analyze attention performance. The most widely used method is EEG. One study used EEG to assess the potential event-related activity in participants during different experiments involving passable transition spaces (Djebbara et al., 2019). The authors found that passable transitions are associated with increased attention processing in the early evoked potential complex. The cortical measures also showed the effect-related properties of the environment guide to visual attention. Two other studies about the same topic explored the effect of furnishings in an interior space by also using EEG (Vecchiato et al., 2015a, 2015b). The results showed that theta oscillations are employed in memory, focused attention, and positive emotions. Hence, the improvement of the theta frontal midline stimulation may be correlated with internalized attention. Attention is also measured with EEG in two other studies that show how EEG-C3-Beta and EEG-CZ-Beta metrics are associated with increased attention and cognitive performance; the high beta band (21—30 Hz) is associated with alertness, whereas EEG-CZ-Highbeta metrics is an indicator of attention judgment (Llinares et al., 2021b, 2021a). These two studies also used heart rate variability (HRV) as a physiological measure because of its relation to attentional control. The metrics were obtained with low frequency (related to sympathetic activity and increased arousal) and high frequency (related to parasympathetic activity and decreased arousal). Apart from studies using EEG, we also found a study that examined the impact of ceiling height and perception of enclosure via 2D stimuli and fMRI (Vartanian et al., 2015). The authors found that curvilinear spaces with high ceilings attractively stimulate neural systems in the attention and visuospatial perception of the dorsal stream, and the anterior midcingulate cortex stimulates and enhances exit decisions in enclosed spaces. Another independent study used a computer analysis to identify a relationship between geometric forms and architectural spaces, their construction materials, and users' consciousness; then, the related user's brainwaves were identified (Elbaiuomy et al., 2018). The authors reported findings for both attention and memory processes, among others. These findings revealed that attention can be enhanced in indoor settings built of concrete, steel, or glass. All the findings of these selected studies that involve improved attentional processes are graphically resumed in Fig. 2.

3.1.2. Memory

Memory is studied in seven of the selected papers using different methods. Two of the studies used psychological memory tasks similar to the Deese, Roediger, and McDermott paradigm experiments (Beato and Díez, 2011). The authors found that cold-hued classroom walls and narrower classrooms are associated with superior memory performance. In addition to psychological tasks, EEG measurements were performed in these two studies to analyze memory performance; these measurements mainly include EEG-C3-Beta and EEG-CZ-Beta metrics, which are associated with cognitive performance, and EEG-F3-Highbeta metrics, which is an indicator of working memory (Llinares et al., 2021b, 2021a). Another study employed a memory-oriented task of recognizing meaningless images to assess the impact of physical surroundings on the memory of persons using the learning space (Xiong et al., 2018). The researchers found that memory is considerably affected by the crossover between lighting and temperature, whereas stimulating participants by increasing the volume of noise does not facilitate memory-oriented tasks. One study used the Wechsler Adult Intelligence Scale-IV (Wechsler, 2005) to assess the impact of classroom lighting on students' working memory (Yang and Jeon, 2020). The authors found that working memory is considerably affected by correlated color temperature and illuminance. This study also revealed a gender bias because women are more sensitive to glare and scored lower than men. The researchers also determined that the influence of optimal correlated color temperature is greater than that of illuminance because the former provides better lighting comfort than the latter. Other researchers investigated the impact of ceiling height on memory in their third experiment via specific tasks (Meyers-Levy and Rui, 2007). They found that low ceilings trigger an impression of confinement. A memory-measure indicator increases the mean number of items recalled by category. On the contrary, spaces with high ceilings stimulate sensations related to freedom. A large retraction clustering is a proven indicator of relational processing. Another study that used computer simulation could identify a relationship between square and cylindrical spaces made of specific alpha waves that can improve the consciousness status of learning depending on memorization (Elbaiuomy et al., 2018). Finally, the impact of color contrast on spatial memory was investigated in the third study (Min and Lee, 2020). Spatial memory was evaluated in terms of scale and object detection rate by requiring the participants to map the space experienced. In this experiment, color contrast and hue do not have a considerable impact on spatial memory. Nevertheless, remarkable memorization of space elements was achieved in high-contrast systems, and a substantial difference in the recall of details related to furniture and lights was achieved when the impact of color hues was contrasted. The results also revealed that compared with cold-color systems, warm- and neutral-color systems improve the spatial memory of the subjects. All the

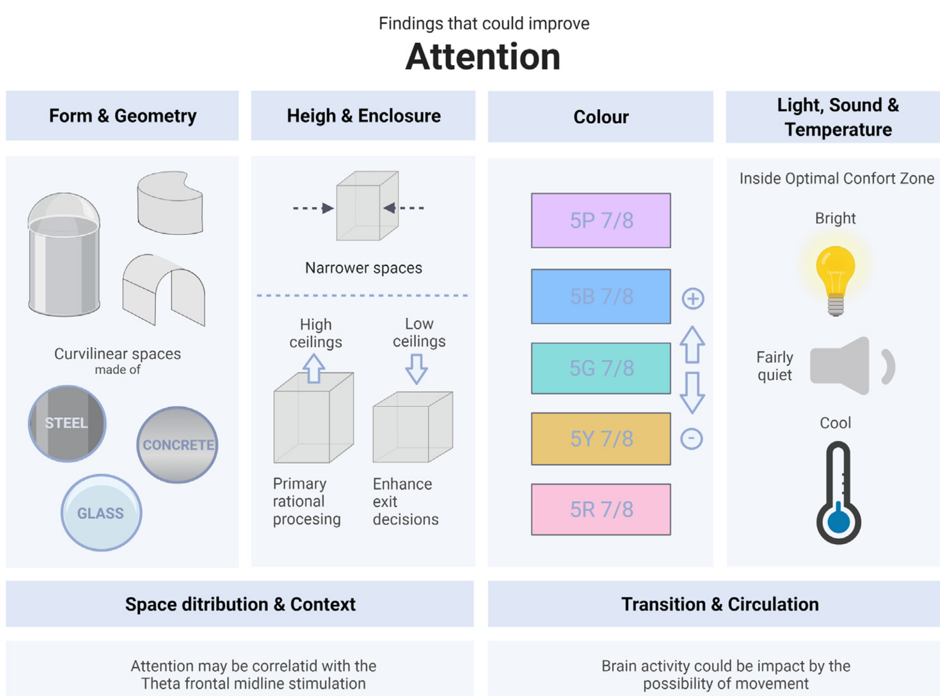

Fig. 2 Graphical abstract of the findings of selected studies about design variables that can improve attention processes (Created with BioRender.com).

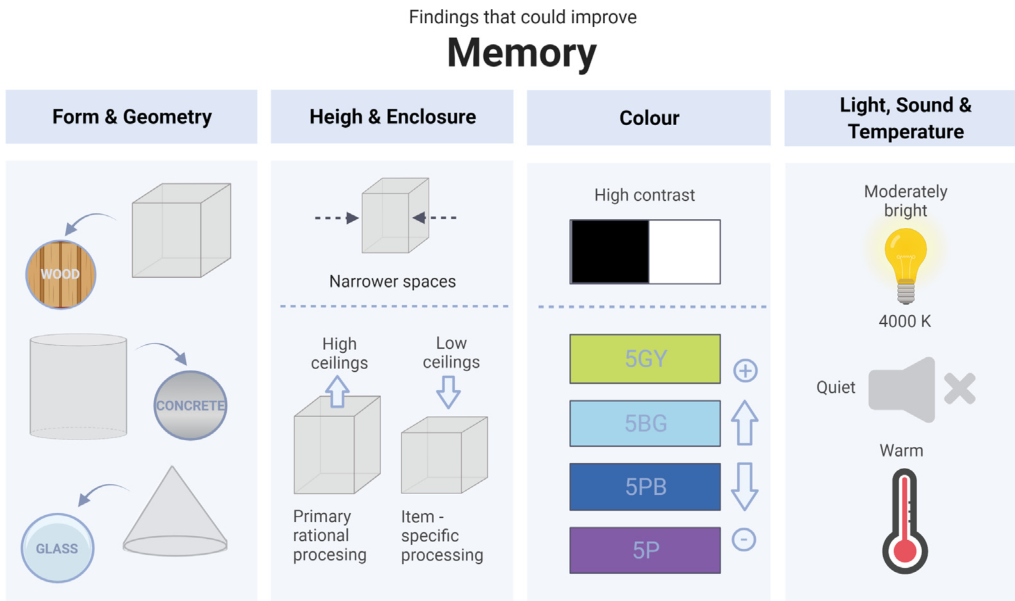

Fig. 3 Graphical abstract of the findings of selected studies about design variables that can improve memory processes (Created with BioRender.com).

findings of these selected studies that show an improvement of memory processes are graphically resumed in Fig. 3.

3.2. Materials (environmental and experimental conditions)

This section considers studies of physical settings. The selected papers focused on specific design variables, such as (1) form and geometry, (2) spatial distribution and context, (3) color and texture, (4) ceiling height, (5) transitivity and circulation, and (6) light, sound, and temperature. Table 3 lists the design variables controlled in the environment and the experimental conditions of each study.

3.2.1. Real-life environment

Eight studies were performed in real learning environments (Table 2). Two studies were conducted in a real-life environment focused on lighting, sound, and temperature (Marchand et al., 2014; Xiong et al., 2018). Another study was performed in an environment-controlled classroom that only analyzed the lighting factors (Yang and Jeon, 2020). These studies are the only ones that reported these parameters in the space (Table 3a). Another study analyzed the impact of wall colors in a real classroom on users' attention (Duyan and Ünver, 2016). In addition to color (hue, value, and saturation), natural and artificial lightings were also controlled in the classrooms to define the experimental conditions. A study of the impact of indoor physical surroundings on learning processes was performed in an environment-controlled university classroom. Another selected study conducted in a real physical room focused on the impact of ceiling height (Meyers-Levy and Rui, 2007). This study was performed in four identical interior spaces, except for their ceiling height. The researchers only reported the height without specifying the width or length of the area. Whether this study was performed in a space where comfort parameters were controlled remains unclear.

3.2.2. Simulation systems

Seven studies were performed with simulation systems (Table 2). One of the selected studies used the 2D images of built, indoor environments inside a room with magnetic resonance imaging (MRI) (Vartanian et al., 2015). No indoor environmental quality (IEQ) data for temperature, light, and relative humidity were reported in this study. However, the MRI room presumably met a minimum of the clinical environment control requirements. Another selected study used computational skills to design a set of six basic geometric forms with the same volume (Elbaiuomy et al., 2018). The researchers reported a natural air environment but without any specifications. The other studies used 3D environments designed with VR techniques (Table 3a). Whether comfort parameters were carefully monitored and controlled during the experiments in these studies is not known. However, one of the research groups reported that all experimental research works were performed in the same place, time slots, and noise and temperature conditions (Llinares et al., 2021b).

3.3. Methods (outcomes)

Given the method used, different outcomes were analyzed across the array of the selected study designs. These reported measurements were classified into subjective and neurophysiological outcomes (Table 2).

3.3.1. Subjective outcomes

Various self-reported measures were used across the array of research designs. These measures consisted of point

Table 3 Experimental studies (a): The population characteristics and environmental conditions recorded in the studies include gender, study size, mean age, standard deviation, methodology, tested variables, and experience method, EEG studies (b): The parameters and conditions from EEG experiments used to report neurophysiological reaction correlations include brand of device, cap analysis software, system type, number of electrodes/channels, sampling rate, band-pass filter, and impedance. The possibility of movement was also recorded because several experiments allowed it, and this approach may have affected the data gathered.

Experimental studies (a), Year	Population				Intervention						
	M	F	Study size	Age ± SD/(Range)	Methodology	Variables being tested	Experience method	Lighting (lux)/(K)/(lm/m^2)	Temp °C	Noise (dB)	Dimension (W x L x H m)/(m^3)
Banaei et al., 2017	7	8	15*	28.6 ± 2.6	EEG & Psychometric	Form and geometry	3D Virtual HTC Vive (head mounted)	NR	NR	NR	5 × 7.5 x 3
Djebbara et al., 2019	11	9	19*	28.1 ± 6.2	EEG & Psychometric	Transition and circulation	3D Virtual Windows Mixed Reality (head mounted)	NR	NR	NR	9 × 5 x NR
Duyan & Ünver, 2016	78	74	152	8–9	Psychometric	Colour and texture	Physical room (real classroom)	500 lm/m^2	NR	NR	NR
Elbaiuomy et al., 2018	–	–	–	–	Simulation software	Form and geometry	CST Microware Studio simulation software	NR	NR	NR	1 m^3
Llinares et al., 2021a	51	39	90	23.56 ± 3.433	EEG & Psychometric	Height and enclosure	3D Virtual HTC Vive (head mounted)	4000 K	NR	NR	16.50 × 8.80 x 3.80
Llinares et al., 2021b	91	69	160	23.56 ± 3.433	EEG & Psychometric	Colour and texture	3D Virtual HTC Vive (head mounted)	4000 K	NR	NR	16.50 × 8.80 x 3.80
Marchand et al., 2014	95	62	158**	(17–49)	Psychometric	Lighting, sound and temperature	Physical room (controlled laboratory)	500/2500 lux	22.2/26.6	35/65	6.4 × 9.4 x 3
Meyers-Levy & Rui, 2007	NR	NR	164	NR	Psychometric	Height and enclosure	Physical room	NR	NR	NR	W x L x 3/2.4
Min & Lee, 2020	39	75	114	22.32	Psychometric	Colour and texture	3D Virtual environment videos Unreal Engine 4.18	NR	NR	NR	15 × 6 x NR/9.5 × 6.5 x NR
Vartanian et al., 2015	6	12	18	23.39 ± 4.49	fMRI & Psychometric	Height and enclosure	2D Image in fMRI Signa Excite HD	NR	NR	NR	NR
Vecchiato et al., 2015a, b	7	5	12	26.8 ± 2.4	EEG & Psychometric	Space distribution and context	3D Virtual CAVE using 3DS Max 2011 software	NR	NR	NR	3 × 3 × 2.5
Xiong et al., 2018	5	5	10	20–24	Psychometric	Light, sound and temperature	Physical room (controlled classroom)	60/300/2200 lux	17/22/27	40/50/60/70	11.7 × 9 x 3
Yang & Jeon, 2020	30	30	60	20–25	Psychometric	Light (illuminance and correlated colour temperature)	Physical room (controlled classroom)	650/1050 lux; 3000/4000/5700 K	25	41	5.22 × 8.17 x 3.4

(*continued on next page*)

Table 3 (*continued*)

Experimental studies (a), Year	Population				Intervention						
	M	F	Study size	Age ± SD/(Range)	Methodology	Variables being tested	Experience method	Lighting (lux)/(K)/(lm/m^2)	Temp °C	Noise (dB)	Dimension (W x L x H m)/(m^3)
EEG studies (b), Year	**EEG parameters & conditions**										
	Brand and software					**Wet/Dry System**	**Sampling rate/ Filtering**	**Nº electrodes/channels**		**Impedance**	**Movement allowed**
Banaei et al., 2017	EASYCAP with EEGLAB					Wet	1000 Hz/ hp = 0.016 Hz; lp = 250 Hz	128		<15 kΩ	No
Djebbara et al., 2019	EegoSports with ANT Neuro and EEGLAB					Dry	500 Hz/ hp = 0.2 Hz; lp = 40 Hz	64		<10 kΩ	Yes
Llinares et al., 2021a, b	b-Alert ×10 with EEGLAB					Wet	256 Hz/ hp = 0.5 Hz; lp = 40 Hz	9		NR	No
Vecchiato et al., 2015a, b	EMicro, EBNeuro with EEGLAB					Wet	256 Hz/ hp = 0.5 Hz; lp = 45 Hz	19/24		<10 kΩ	No

NR = Not reported.

scales, questionnaires, analysis of spatial mapping, Stroop Color and Word Test (Stroop, 1935), Self-Assessment Manikin (SAM; Bradley and Lang, 1994), Bourdon Attention Test (Grewel, 1953), and semantic differential. Seven of the fourteen selected studies used these subjective outcomes in addition to neurophysiological outcomes, whereas six studies used only these psychometrical methods. Another study also analyzed behavioral data by recording the reaction time (Djebbara et al., 2019). Experience, dominance, arousal, novelty, familiarity, comfort, mood, pleasantness, beauty judgments, and approach-exit decisions were the dimensions considered in these measures. The outcomes of these studies were obtained posttest or during exposure, except for the outcomes of one study without participants. Additionally, one study assessed attention using the Stroop virtual test (Banaei et al., 2017), whereas the other two studies measured the sense of presence through a SUS questionnaire (Llinares et al., 2021b, 2021a). Different types of tasks were used in some studies with different objectives. In one study (Marchand et al., 2014), a test passage and a comprehension assessment were performed using a sentence verification task (Royer et al., 1979). This study also performed specific learning tasks of listening and reading, whereas another study performed different categorization, attention, memory tasks, and other subjective outcomes (Meyers-Levy and Rui, 2007). Another study required participants to sketch the proportion, size, and shape of the experienced environment and its furniture to analyze spatial memory (Min and Lee, 2020).

3.3.2. Neurophysiological outcomes

All the studies performing neurophysiological methods also used psychological methods, except for one study that was conducted without population (Table 3a). Two of these studies observed the correlations between the psychological and neurophysiological metrics (Llinares et al., 2021b, 2021a). This approach constitutes relevant progress in the neuroarchitecture field. Regarding the methodology used, the most common practice used to measure objective neurophysiological response is EEG techniques (Table 3b). Wet electrode systems (EB Neuro, EASYCAP, b-Alert x10, and BEMicro) were used in five of the studies, and only one study used a dry electrode system (EegoSports). The EEG studies and their data collection, protocols, and devices/technology used for each study are shown in Table 3. The band-pass filter data and sampling rates are diverse across the publications, whereas the number of electrodes varies from 9 to 128. These differences indicate various neurophysiological data collection methods used across the selected studies. However, the impedance was kept below 10 (Djebbara et al., 2019; Vecchiato et al., 2015b) and 15 kΩ (Banaei et al., 2019). Another method of compiling central neural system data used is fMRI (Vartanian et al., 2015). One study also explored the impact of geometric spaces and their construction materials on users' brainwaves via computer software (CST Microwave Studio) (Elbaiuomy et al., 2018). The results of these studies cannot be compared because different techniques were used in each study.

Table 4 Findings of selected studies after qualitative review according to tested variables that affect memory and attention: (1) form and geometry, (2) space distribution and context, (3) color and texture, (4) height, width, and enclosure, (5) transition and circulation, (6) light, sound, and temperature.

Studies		Findings	
Reference	Variable	Attention	Memory
Banaei et al., 2017	Form and geometry	Curvilinear interior spaces cause higher cognitive and emotional levels whereas rectilinear interior spaces contribute to lower satisfaction and excitement in participants.	NS
Djebbara et al., 2019	Transition and circulation	Early sensory brain activity varies as a function of affordances when discovering the environment and before actual movement. Movement preceded by negative, motor-related component is dependent on affordances.	NS
Duyan & Ünver, 2016	Colour and texture	Students' attention is higher when walls are purple (5P 7/8), followed by blue (5B 7/8), green (5G 7/8), yellow (5Y 7/8) and red (5R 7/8).	NS
Elbaiuomy et al., 2018	Form and geometry	Attention is enhanced in an indoor space built of steel, concrete, or glass.	Memory can be enhanced in a square or cylinder space built of concrete. Conical, glass spaces and square, wooden spaces are better for concentrating and retaining information.
Llinares et al., 2021a	Height and enclosure	The classroom width significantly impacts on psychological and neurophysiological attention metrics. Wider classrooms are associated with poorer performance and lower emotional arousal. Psychological and neurophysiological metrics are correlated.	The classroom width significantly impacts on psychological and neurophysiological memory metrics. Wider classrooms are associated with poorer performance and lower emotional arousal. Psychological and neurophysiological metrics are correlated.
Llinares et al., 2021b	Colour and texture	Student's attention tasks have higher results in classrooms with cold-hued colors (between yellowish green and purple, 5GY, 5BG, 5 PB, and 5P). Neurophysiological results indicated that cold-hued colors elicited significantly higher activation.	Student's memory tasks have higher results in classrooms with cold-hued colors (between yellowish green and purple, 5GY, 5BG, 5 PB, and 5P).
Marchand et al., 2014	Light, sound and temperature	Conditions of T°C, sound and light outside the comfort zone (OCZ) affects listening tasks negatively but has no impact on reading tasks.	NS
Meyers-Levy and Rui, 2007	Height and enclosure	NS	Ceiling height can influence specific concepts: space with high ceiling stimulates primarily rational processing; and space with low ceiling stimulates item-specific processing.
Min and Lee, 2019	Colour and texture	NS	Memory is enhanced in spaces with high-contrast colour combinations.
Vartanian et al., 2015	Height and enclosure	Spaces with a high ceiling and curvilinear geometry are more	NS

(*continued on next page*)

Table 4 (*continued*)

Studies		Findings	
Reference	Variable	Attention	Memory
		attractive and stimulate areas involved in visual and spatial perception. Restricted movement and restricted fields of vision, as in spaces with low ceilings, prompt emotional responses that enhance exit decisions.	
Vecchiato et al., 2015a, b	Space distribution and context	Internalized attention may be correlated with the improvement of the theta frontal midline stimulation. During focused attention, memory and positive emotion process, the Theta neuronal oscillations are employed.	NS
Xiong et al., 2018	Light, sound and temperature	Thermoneutral, fairly quiet, and moderately bright are the optimal physical condition for problem-solving processes, whereas cool, fairly quiet and bright are the optimal physical conditions for attention-oriented tasks.	Thermoneutral, quiet and bright are the optimal physical conditions for perception-oriented tasks, whereas warm, quiet and moderately bright are the optimal physical conditions for memory-oriented tasks.
Yang & Jeon, 2020	Light, sound and temperature	NS	The optimal colour temperature lighting comfort for learning spaces is 4000 K. Satisfaction, acceptance, and perception are not affected. Women are more sensitive to glare. Optimal colour temperature has more impact on learning than illuminance.

NS = Not Studied.

3.4. Population

Participants were not filtered by gender, age, or cultural background during the selection process (Table 3a). In total, 972 individuals participated in the experimental studies. Population characteristics are shown in Table 3. Only six of the selected studies showed the average age (Banaei et al., 2017; Djebbara et al., 2019; Llinares et al., 2021b, 2021a; Min and Lee, 2020; Vartanian et al., 2013, 2015). One of them did not calculate the standard deviation (Min and Lee, 2020). All of these studies were performed with university students, except for the one that involved primary school students (Duyan and Ünver, 2016), and another study, which used computational skills with no participants (Elbaiuomy et al., 2018). Therefore, we analyzed different age ranges in this review (see Table 3). Ethnic and cultural precedence was described only in one study (Marchand et al., 2014). In the other two studies, the precedence was a criterion used to avoid any cultural effects (Llinares et al., 2021b, 2021a). In another study, participants were classified by sociocultural and economic backgrounds (Duyan and Ünver, 2016). Participant eligibility criteria comprise common and general standards and some specific requirements. In seven studies, normal or corrected-to-normal vision was specified for the subjects (Banaei et al., 2017; Djebbara et al., 2019; Llinares et al., 2021b, 2021a; Vartanian et al., 2013, 2015; Yang and Jeon, 2020). Three studies performed pretest screenings, one of which revealed a color-blind participant (Duyan and Ünver, 2016; Min and Lee, 2020; Yang and Jeon, 2020). One study required specific conditions, such as enough sleep, regular diet, and clothing, to minimize individual differences (Xiong et al., 2018). Two studies required self-assessed right handedness (Vartanian et al., 2013, 2015). Without further explanation, the subjects in five studies were described as "healthy" or "neurologically healthy" (Banaei et al., 2017; Djebbara et al., 2019; Vartanian et al., 2013, 2015; Vecchiato et al., 2015a, 2015b). In four of all the studies, the participants were remunerated (Djebbara et al., 2019; Meyers-Levy and Rui, 2007; Min and Lee, 2020; Yang and Jeon, 2020). Only one study required participants to have previous experience or exposure to avoid the effects of environmental inadaptability (Xiong et al., 2018). Three studies specified the academic background (Djebbara et al., 2019; Zou et al., 2019) or the grade point average of the participants (Park and Choi, 2014). In all 14 selected publications, the average number of subjects is 81 (SD, 65.8). The use of statistical analysis to assess the appropriate number of subjects for valid statistics is not documented in any study. Only two publications identified ρ-value and z-score (Vartanian et al., 2013, 2015), whereas ρ-value and correlation coefficients were reported in five EEG publications (Banaei et al., 2017; Djebbara et al., 2019; Llinares et al., 2021b, 2021a; Vecchiato et al., 2015b). One study reported Cronbach α values to ensure the reliability of the measurement scale (Leung and Fung, 2005). Another study used ARC scores and p values to determine the clustering ratio (Meyers-Levy and Rui, 2007). The remaining studies only presented p values (Marchand et al., 2014; Min and Lee, 2020; Park and Choi, 2014).

3.5. Interventions (variables tested)

Different variables were tested across the array of the selected studies. These variables were grouped as follows: (1) form and geometry, (2) space distribution and context, (3) color and texture, (4) height, width, and enclosure, (5) transition and circulation, and (6) light, sound, and temperature. Finally, the results of the selected studies are listed in Table 4 according to the variables tested (see Table 4).

3.5.1. Form and geometry

Two studies demonstrated the impact of form or interior space geometry on cognition. One used EEG combined with psychometric methods, and the other used computational software. In one of the studies, the subjects were requested to move across the simulated spaces to experience the space from various viewpoints (Banaei et al., 2017). The subjective psychometric findings showed that rectilinear interior spaces contribute to low satisfaction and excitement in participants, whereas spaces with curved lines result in high scores in these two cognitive—emotional states. The second study examined the impact of six types of interior space geometries and four different building forms on users' brainwaves (Elbaiuomy et al., 2018). The studied forms, which have the same volume, were a cube, cone, pyramid, cylinder, vault, and dome. In this study, resonance frequency was identified in various interior spaces using CST Microwave Studio. The authors found a relationship between the geometric forms of interior spaces, their construction materials, and users' consciousness. In this study, the associated user's brainwaves were discerned, and the findings revealed that attention can be enhanced by indoor settings built of steel, concrete, or glass. As a function of memory, learning can be enhanced if participants are inside a square or cylindrical space made of concrete. Moreover, the cognitive processes involved in concentration and retaining information can be enhanced if the user is inside a conical space, glass space, or a square, wooden space.

3.5.2. Space distribution and context

Only two studies, performed by the same authors, used EEG as an objective indicator to investigate the impact of the style and distribution of furnishings in interior spaces (Vecchiato et al., 2015a, 2015b). The context was defined as "empty," "modern," or "cutting-edge." Both publications used independent component analysis with only artifact-free trials considered in the studies. Time-frequency evaluation and topographical statistical maps were used to measure power spectral density on individually defined bands and widths that used the individual alpha frequency (IAF): θ (ranging from IAF $\times$ 0.4 to IAF $\times$ 0.8) Hz, α (IAF $\times$ 0.8, IAF $\times$ 1.2) Hz, and μ (IAF, IAF $\times$ 1.2) Hz bands. Mass univariate analysis reported high θ strength in the left and frontal areas in interiors with self-reported height presence scores. α and μ band stimulation was reported but not sustained throughout the frontal and central areas. The increased activity of θ in the frontal midline and the major loss of synchronization in the frontal and left μ band were correlated with height comfort scores. The authors concluded that visual and spatial perception areas in the front-parietal system are stimulated by the perception of a nice interior, indicating the involvement of cognitive and motor processes throughout the assessment of built environments.

3.5.3. Color and texture

Three studies showed how color and/or texture considerably affect memory and attention using psychometric methods. Only one of them used neurophysiological methods, including HRV and electroencephalogram. The first study explored the influence of color contrast and hue on spatial memory (Min and Lee, 2020). Six indoor settings, each in a different color (neutral, cool, and warm color variations, with high and low contrast), were shown as stimuli to participants. The results revealed that memory is enhanced in spaces with high-contrast color combinations. High contrast increases visual saliency, encourages perception, and improves the understanding of unfamiliar spaces and embedded architectural elements. The results also indicated that color contrast in a short evaluation of spaces leads to spatial memory and cognition. The second study explored the effect of the color of classroom walls on students' attention (Duyan and Ünver, 2016). The experimental method in this study used the students' preferred wall colors from a previous study (Duyan & Ünver, 2015) to select and apply five colors defined by the Munsell color system (Munsell, 1971) into a classroom wall for one week. The students' attention was assessed at the end of every week. The results revealed that the students' attention levels increase with purple (5P 7/8) walls, followed by blue (5B 7/8), green (5G 7/8), yellow (5Y 7/8), and red (5R 7/8) walls. Thus, the best outputs were achieved with the cold-hue colors. These findings are in good agreement with those of the third study, which showed that cold hue colors increase arousal and enhance performance in attention and memory tasks. This study measured the impact of cold and warm hue—colored virtualized classroom walls on attention and memory processes (Llinares et al., 2021b). The stimuli included 24 configurations defined by four cold and four warm colors with different chromas: 5GY 5/4, 5GY 5/10, 5BG 5/4, 5BG 5/10, 5 PB 5/8, 5 PB 5/14, 5P 5/6, 5P 5/12, 5RP 5/8, 5RP 5/14, 5R 5/10, 5R 5/16, 5 YR 5/4, 5 YR 5/10, 5Y 5/2, and 5Y 5/8.

Study		D1	D2	D3	D4	D5	Other	General
Banaei, M., et al.	2017	?	-	+	-	-	?	?
Djebbara, Z., et al.	2019	-	?	+	-	-	?	?
Duyan, F. & Ünver, R.	2016	?	?	-	-	+	?	?
Elbaiuomy, E., et al.	2018	-	-	-	-	-	-	-
Llinares, C, et al.	2021a	-	-	-	-	-	-	-
Llinares, C, et al.	2021b	-	-	-	-	-	?	-
Marchand, G. C., et al.	2014	?	?	-	-	-	-	-
Meyers-Levy, J., Rui, Z.	2007	-	?	-	-	+	?	?
Min, Y. H., Lee, S.	2019	?	-	-	-	-	?	-
Vartanian, O., et al.	2015	?	-	-	-	-	-	-
Vecchiato, G., et al.	2015a	?	-	-	-	-	?	-
Vecchiato, G., et al.	2015b	?	-	-	-	-	?	-
Xiong, L., et al.	2018	-	?	-	-	-	-	-
Yang, W. & Jeon, J.	2020	-	?	-	-	-	-	-

+ High risk of bias   ? Unclear risk of bias   - Low risk of bias

Figure 4 Analysis of types of bias found in the selected studies caused by the following: randomization process (D1), deviations from intended interventions (D2), missing outcome data (D3), measurement of the outcome (D4), selection of the reported results (D5), other important/key contamination bias, such as the IEQs (D6).

3.5.4. Height, width, and enclosure

Three studies showed the considerable impact of ceiling height, width, and enclosure using two different environments: virtual and real spaces. The first study was conducted in a real environment, and it demonstrated how ceiling height affects the way information is interpreted by the users of the space (Meyers-Levy and Rui, 2007). This study, which was focused on height, was based on three different experiments performed in four rooms with identical features, apart from their ceiling height. Experiment 1 used body state assessment and anagram solving to show that ceiling height can influence specific concepts. Experiments 2 and 3 also demonstrated that the factors affected by ceiling height mainly elicit rational rather than item-specific processing. Variations in the form of perception and responses of individuals occurred only when the perception of the ceiling height was relatively high. Other proofs that relational (item-specific) processing can be boosted by concepts primed by a high (low) ceiling were added during the experiment by analyzing the memory measures of cud-item recall and recall clustering. The results consistently showed these two types of processing with highly accurate indicators. The second study, focused on width, was performed in virtual environments and showed that narrow classrooms enhance cognitive performance, which is associated with high arousal levels (Llinares et al., 2021a). The impacts of different parameterizations of classroom width (8.80, 8.20, and 7.60 m) with the same length (16.50 m) and height (8.80 m) dimensions were compared. Finally, the third study, focused on height and enclosure, examined the impact of these variables on attention by using 2D stimuli in fMRI (Vartanian et al., 2015). The study produced behavioral results by evaluating the participants' preferred approach/avoidance and beauty judgments. Neural results were also reported using fMRI analysis with statistical parametric mapping. The left precuneus and left middle frontal gyrus were enabled by aesthetic decisions related to ceiling height comparison. The left middle temporal and right superior temporal gyrus were stimulated by appraisals of beauty when comparing open/closed spaces. Activity was observed in the anterior cingulate cortex when contrast was experienced in open/enclosed settings. Spaces with a high ceiling and curvilinear geometry were regarded as attractive and stimulating and involved in visual and spatial perception. The anterior midcingulate cortex was enabled by enclosed spaces, which enhance exit decisions. The researchers argued that low locomotive and visual availability, such as in spaces with a low ceiling, incite emotional responses that enhance exit decisions.

3.5.5. Transition and circulation

As far as we know, only one study analyzed the effect of transition and circulation on cognitive processes. Thus, this investigation explored the impact of the cognitive processes associated with architectural affordances (environment and movement) using EEG (Djebbara et al., 2019). The experiment used VR to perform transitions ranging from nonpassable to easily passable spaces. The subjective experience was measured via a virtual SAM and reaction time. The results showed that the early sensory brain activity of each person varies depending on affordances when these individuals perceive the world and before an actual movement. These results also showed that the motor-related, negative component depends on affordances that proceeded movement through transitions. These findings suggested that awareness is intrinsically connected to the body's possible movement and proved that space movement is a continuous predictor of the universe of affordances.

3.5.6. Light, sound, and temperature

Several studies also demonstrated how light, sound, and temperature considerably affect attention and/or memory (Table 4). A study examined whether undergraduate students' learning, mood, and perceptions of learning spaces have any impact on success in reading and listening tasks affected by combinations of comfort variables, such as temperature, sound, and light (Marchand et al., 2014). The results showed that in a comprehension test, subjects who experienced the listening task outside the comfort zone have more negative grades than subjects who were in normal comfort conditions. However, no discrepancy between reading modality conditions was observed. Compared with the students in their usual comfortable conditions, the students outside of their comfort zone show increased negative effects and claim that the classroom temperature and sound have a considerable adverse influence on their results. The results of the participants in the reading task scenario are better than those of the students in the listening task scenario because of the poor performance of the task with the sound levels in the classroom. Another study examined the effect of light, temperature, and sound on the learning process in different types of tasks (perception, memory, attention, and problem solving) with a $3 \times 4 \times 3$ full factorial design experiment (Xiong et al., 2018). This study showed that environmental factors have a considerable impact on the learning processes except in problem-solving tasks. According to this study, the optimal physical learning space varies for each type of learning process: thermoneutral, quiet, and bright conditions for perception-oriented tasks; warm, quiet, and moderately bright conditions for memory-oriented tasks; thermoneutral, fairly quiet, and moderately bright conditions for problem-solving processes; and cool, fairly quiet, and bright conditions for attention-oriented tasks. Finally, the last study examined the impact of color temperature and classroom lighting illuminance on students' cognition and perception (Yang and Jeon, 2020). The experiment was performed using the light of different color temperatures (3000, 4000, and 5700 K) and illuminance (650 and 1050 lx). The researchers found that the color temperature for optimal lighting comfort in learning spaces is 4000 K. However, satisfaction, acceptance, and perception are not affected. The results revealed a gender bias in the working memory task because women are more sensitive to glare and achieved lower scores than men. The researchers concluded that optimal color temperature has a more considerable effect than illuminance because it gives a great sensation of comfort.

3.6. Control/comparator

A clear distinctive control was used in the six studies of exposure to the built environment. This approach included the following: the study that explored the impact of furnishing style by comparing an "empty room" to "modern" and "cutting-edge" interior spaces (Vecchiato et al., 2015b); the study that investigated the impact of geometric form by comparing a simple cubic space to 17 alternative spaces with diverse geometries (Banaei et al., 2017); those that explored the impact of light, sound, and temperature on learning processes (Marchand et al., 2014; Xiong et al., 2018); and the study that analyzed the effect of contrast and color upon spatial memory (Min and Lee, 2020). No clear exposure to controlled, interior, built environments was found in the remaining four publications. Instead, the following experimental studies manifested differences between groups: the study that examined an open/enclosed high space and an open/enclosed low space (Vartanian et al., 2015); the study that explored the processing type that people use by comparing four rooms with ceilings of different heights (Meyers-Levy and Rui, 2007); the one that studied the attention and memory performance of university students in different classroom widths (Llinares et al., 2021a); the study that investigated the cognitive processes associated with architectural affordances using nonpassable to easily passable transition spaces (Djebbara et al., 2019); the study that explored the impact of geometric interior spaces and their construction materials on brainwaves and on the perception of subjects in six settings with identical volume but different geometrical form (Elbaiuomy et al., 2018); the study that analyzed the impact of classroom walls of five different colors on students' attention (Duyan and Ünver, 2016); and the study that explored the impact of cold or warm hue classroom walls on university students' memory and attention (Llinares et al., 2021b).

3.7. Risk of bias

The risk possibility of the experimental methodologies included in this review must be analyzed to understand the quality of the studies. The Cochrane tool (Higgins et al., 2011) for evaluating the risk of bias (Fig. 4) was applied, and five types were determined for discussion. One study was excluded from this analysis because of the lack of experimentation in its materials and methods (Elbaiuomy et al., 2018).

Seven of the fourteen studies did not reveal how the allocation of interventions was defined, resulting in an unclear risk. Only four groups of researchers reported that the stimuli performed was rotated in a random order of exposure (Djebbara et al., 2019; Llinares et al., 2021b, 2021a; Yang and Jeon, 2020). In another study, the authors reported that the experiment was conducted independently and without order effect (Xiong et al., 2018). Another study described some phases of its experimental procedure as 50/50 pseudorandomized or randomized (Marchand et al., 2014).

All experimental studies, except one (Marchand et al., 2014), sampled participants individually. Therefore, the probability of subjects who were aware of possible classification (e.g., by background) was reduced. Whether the subjects participated blind in the experiments is not known. Moreover, whether the staff conducting the experiment were unaware of participant classification and the exposure sequence is uncertain. The studies included exposure to control, but five of them did not explain this scenario clearly. These studies showed the differences between groups, whereas this study revealed the differences between groups.

The problem of incomplete data is mentioned in two publications, addressing possible loss bias. These studies stated that certain participants were excluded because of technical problems with data collection and unnecessary noise in the data analysis.

No noteworthy risk was found in the measurement of the outcome.

Two studies revealed an unclear risk of reporting bias because only significant results were reported in the papers (Duyan and Ünver, 2016; Meyers-Levy and Rui, 2007). Ten papers reported insignificant findings alongside significant findings, thereby reducing the risk selective of reporting. The remaining study did not use statistical methods.

Finally, the IEQs of the built environments experienced were only reported in one study as a key contamination consideration (Djebbara et al., 2019) and in three studies as the main variable that has been tested (Marchand et al., 2014; Xiong et al., 2018; Yang and Jeon, 2020). Finally, another study performed in real-life classrooms reported controlling only the lighting (Duyan and Ünver, 2016). The features referred to as IEQ variables play an essential role in the environmental experience. Therefore, a high risk of biased outcomes exists when these variables are not controlled and stabilized. A study in a clinical fMRI setting can be reasonably assumed to have a degree of control, whereas the other study performed in a laboratory environment indicated that all noise and temperature conditions were kept stable (Llinares et al., 2021b). Uncontrolled IEQ parameters entail a considerable risk that the impact reported in the papers is biased (Vartanian et al., 2013, 2015).

4. Discussion

Neurophysiological and/or psychological methods were used in the present study to examine whether the current literature about the features of the interior and built environments can demonstrate any impact on human cognition (see Table 2). Six of the spatial properties addressed in the selected articles were examined (see Table 4): (1) form and geometry, (2) space distribution and context, (3) color and texture, (4) height, width, and enclosure, (5) transition and circulation, and (6) light, sound, and temperature. However, the possibility of unexplored synergistic effects among the design variables was not yet addressed, and this aspect must be investigated in future research.

Five limitations in this field were identified: (1) diverse methods (outcome, measure, and system types), procedures (filters, impedance, and sampling rate), and algorithms (interfaces/transformations of data output) for objective data decoding; (2) inaccurate documentation of the characteristics of participants; (3) failure to specify the procedure and reason for measuring sample size; (4) p values described without correlating coefficients or extent of impact; (5) no description of any controlled IEQ variables. The first limitation shows that no studies used the same method to quantify or record the impact of built environment design on cognitive processes. The use of different methods limited the capacity to synthesize and confirm by replicating the results. In addition, different environmental conditions (real or simulated) do not help achieve a standard or cross-validated protocol. Data were also presented in different ways because of the multiple methodologies used. Some publications used plotted results, which are visually clearer and more straightforward than bar charts. Thus, this limitation also identified the use of different methods of statistical analysis, which constitutes a reproducibility challenge. However, this problem is not uncommon in cognitive neuroscience. Heavy reliance on statistical measurements to isolate multivariate data indicates that great consideration is needed for experimental designs to yield consistent findings. The second to the fourth limitations feature a substantial underempowerment in the studies because they only include an average of 81 participants and a minor shift in age samples. Whether this young pool of subjects is due to age-related experimental intentions or merely due to all participants being selected from educational establishments is unclear. This scenario also indicates a population with a level of schooling above the world average. Based on the small sample size, p values should be displayed along with the extent of the impact or correlation coefficient values. Finally, the last limitation indicated that among the studies using simulation system methods, only six reported controlled environmental parameters, such as IEQs (see Table 3a). This lack of control of IEQ parameters limits the consideration of important design elements, such as light, orientation, and ventilation. Future research methodology must closely examine how the application of technologies interacts with objective measurement systems to simulate a monitored built environment.

In some studies, experiences were also analyzed in relation to the body movements of the participants (Vecchiato et al., 2015b). The researchers found that cognition processes are inherently related to the possibilities of future body movement. These findings showed that moving through environments may create an ongoing prediction of a universe of affordances. T his study also demonstrated the probability of assessing EEG correlates of spatial perception, including sensorimotor, embodiment, and spatial experimentation of cerebral schemes. Thus, this study revealed the involvement of motor processes in cognitive processes in the perception of built environments. Therefore, considering an in-depth analysis of the impact of the action, movement, and spatial continuity on cognition processes is valuable for future research.

From a methodological point of view, the results demonstrated that a limited number of studies had been conducted in this field of knowledge thus far. Thus, the experiments have limited sample sizes and no group variety. Various methodological, technological, and statistical methods were also used (see Table 3a). Finally, no studies have documented the dimensions of the impact according to these limits, indicating that a meta-analysis of this field of study is not yet feasible. Some studies that used neurological methods analyzed the main cortical surface areas to measure the activity caused by visual stimulation situated in the occipital and parietal regions for visual input and identifying objects, respectively (see Table 3b). Thus, experiments using head-mounted VR devices should not hinder the EEG electrodes under the scalp areas, where such neural activity is predicted. Therefore, using a head-mounted display (HMD) compatible with the EEG electrodes is vital to ensure a stable experimental design. HMD systems are preferred because of the CAVE system (Cruz-Neira et al., 1992). The research into advanced EEG and fMRI modeling provides a deep understanding of the neuronal circuits, networks, and mechanisms stimulated during perception and cognitive response tasks. These approaches would definitely require cortical/subcortical networks. In particular, three studies identified the anterior cingulate cortex, which has important limbic and prefrontal links in both EEG and fMRI results. The posterior cingulate cortex and the occipital lobe are involved when processing multiple spatial perspectives.

Other instruments based on physiological methods (e.g., galvanic skin response and blood pressure) are valuable for assessing the body's response to a stimulus. In this approach, reliable and calculated experimental comfort conditions are required to guarantee that the responses are caused by the stimuli being evaluated instead of other confusing parameters. Although the outcomes in this method include evidence about how the body identifies and reacts to visual stimulation, they are not as effective as the single outcome for discerning how, where, and why brain stimulation happens. These instruments are also ideal for verifying the presence of a reaction, whereas fMRI or EEG may indicate what activity occurs in the central neural system. However, only two of the selected studies applied these physiological methods (HRV) (Llinares et al., 2021b, 2021a). These types of outcomes, both neurophysiological and psychological, must be integrated to help determine if the subject is actively aware of a shift in cognitive status in response to stimuli.

5. Conclusion

The results of this review suggest the following: (i) Form and geometry could enhance the attention processes in curvilinear interior spaces built of steel, concrete, or glass, whereas memory processes could be enhanced in a square or cylinder space built of concrete. (ii) When a subject assesses space distribution and context, the front-parietal system is stimulated. Thus, the mental process involving this assessment task could have an impact on attention. (iii) The use of a cold-hue color in classroom walls could enhance memory and attention, whereas the use of high-contrast color combinations could improve spatial memory. (iv) Attention could be improved in narrow classrooms with high ceilings and curvilinear geometry, whereas memory could be improved in narrow classrooms with low ceilings. (v) Transition and circulation affordances could be connected with awareness and cognitive processes. (vi) Light, sound, and temperature conditions could enhance the attention processes in cool, fairly quiet, and bright spaces, whereas memory could be improved in warm (4000 K), quiet, and moderately bright spaces. However, robust evidence regarding the neuropsychophysiological impact of different variables related to learning spaces and the design of built, indoor environments remains lacking. One group could observe the correlation between psychological and neurophysiological metrics, representing substantial progress in the field of neuroarchitecture (Llinares et al., 2021b, 2021a). However, no accepted standard approaches or protocols exist at present to determine how the design factors of built environments influence the neurophysiological correlates of human cognition processes. This situation has resulted in various strategies and methods that make producing a meta-analysis of the impact unfeasible in terms of reviewing studies at the state-of-the-art level (see Table 3a). Extensive research with controlled documentation of environmental factors is needed to assess the impact of design variables on neuropsychophysiological reactions and their synergistic effects and make progress in this field. The reasons why different levels of cognition occur in different built environments should be considered. Moreover, determining whether the neurophysiological processes involved in self-reported feelings and subjective decisions affect our levels of attention and memory in different spaces is essential. Given that a clear consensus about the methods that analyze the built environment's impact on the cognitive processes does not exist, neurophysiological analysis, an area in which architects do not have the expertise, must be performed soon. Standard protocols must be created to quantify and determine the cognitive effect of how interior spaces are perceived, enabling a clear understanding of the impact that the design variables of interior spaces have on attention and memory. In addition, research must use standard criteria when reporting experimental design parameters to ensure maximum clarity and reproducibility. New principles for the design of environments and spaces in all sectors (education, healthcare, and industry) could change how governments and industries worldwide value the project design of spaces by drawing up a replicable and cross-validated approach applicable when assessing spaces with arbitrary post-occupancy instruments. If the impact of design variables is understood from a neurophysiological approach, architects will have a leading role in supporting and boosting education, work productivity, and other human activities affected by their surroundings.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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