Frontiers of Architectural Research 12 (2023) 575—586

Higher Education Press

Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.keaipublishing.com/foar

SOUTHEAST UNIVERSITY

RESEARCH ARTICLE

Lighting, colour and geometry: Which has the greatest influence on students' cognitive processes?

María Luisa Nolé Fajardo [a,*], Juan Luis Higuera-Trujillo [a,b], Carmen Llinares [a]

[a] *Instituto Universitario de Investigación en Tecnología Centrada en el Ser Humano (HUMAN-tech), Universitat Politècnica de València, Valencia 46022, Spain*
[b] *School of Architecture, Art and Design, Tecnologico de Monterrey, Monterrey 64849, Mexico*

Received 14 October 2022; received in revised form 17 January 2023; accepted 15 February 2023

KEYWORDS
Classroom design;
Memory;
Attention;
Preference;
Virtual classroom

Abstract Many studies have analysed the effects that design elements, such as lighting and colour, have on students' cognitive functions. These analyses, while providing useful information, do not allow researchers to compare the effects of multiple design elements. The objective of the present study is to analyse the relative influence of lighting, colour and geometry on attention and memory, the main cognitive functions that underlie learning, and on preference. In a controlled, virtual reality (VR)-based experiment, 200 university students (100 male/100 female) performed attention, memory and preference tests in classrooms with different configurations of lighting (colour temperature and illuminance), colour (saturation and hue) and geometry (height and width). The results identified significant gender-based differences, which demonstrates the need to segment, by gender, samples in this type of study. Lighting had the greatest influence, significantly affecting males' memories, females' attention and the preferences of both genders. Colour was also an influential element, significantly affecting females' attention, while geometry was the least influential. Finally, it should be highlighted that attention was the metric most sensitive to design variations. These results may be of interest to architects, interior designers and engineers who wish to create classrooms that satisfy students' psychological needs.

---

* Corresponding author.
E-mail address: mlnole@i3b.upv.es (M.L. Nolé Fajardo).
Peer review under responsibility of Southeast University.

https://doi.org/10.1016/j.foar.2023.02.003

1. Introduction

Research into human behaviour in built environments is based on the notion that environments have a continuous influence on people (Karakas and Yildiz, 2020). Many studies in the field have tried to identify classroom designs that enhance students' behaviours (Rigolon and Alloway, 2011). Lighting, colour and geometry are among the interior design elements studied in the field of teaching–learning.

Lighting is among the most studied elements. It has been found that lighting is positively related to students' concentration (Sleegers et al., 2013). In examinations into artificial lighting, two variables must be taken into account, that is, illuminance and colour temperature (CCT). Overall, the results of previous studies have shown that low illuminance is related to lower cognitive and academic performance (Hathaway, 1995), and that increased illuminance is associated with better performance in attention and memory tests (Llinares et al., 2021a; Smolders and de Kort, 2014). In a specific university environment, Marchand et al. (2014) found that, in a space classified as "uncomfortable" (illuminance of 2500 lx), university students achieved lower scores in a reading comprehension test than students who took the test in a space with an illuminance level classified as "comfortable" (500 lx). Examinations into CCT have, as yet, produced no conclusive results. For example, some authors have observed that higher CCT produces higher cognitive processing and better concentration (Keis et al., 2014; Mills et al., 2007; Viola et al., 2008), while others have concluded that CCT has no influence on attention (Smolders and De Kort, 2017) or memory (Vandewalle et al., 2007).

Colour is another frequently analysed design element. Previous studies have shown that fewer errors are made in text correction tasks (Kwallek et al., 1996), and that tasks are completed quicker (Cockerill and Miller, 1983) in chromatic spaces than in achromatic or white spaces. As to hues, study results have shown that cool hues improve university students' attention and memory (Llinares et al., 2021b) and the performance of complex tasks (Xia et al., 2016). A longitudinal study showed that a school classroom with green coloured walls improved results in a specific test of sustained, selective attention (Bernardo et al., 2021). Another colour element that must be taken into account is saturation, which, despite being of great importance in subjective assessments of spaces, has been very little studied, in isolation, in educational environments (Gao and Xin, 2006). In general, people prefer classrooms with saturated colours (Cubukcu and Kahraman, 2008).

Another key classroom design element is their dimensions. Ahrentzen and Evans (1984) found that classroom ceiling height was positively correlated with teacher satisfaction. On the other hand, Readand Sugawara (1999) found that school-age children cooperated better in classrooms with lower ceilings. Earthman (2004) noted that classrooms with high ceilings could negate the benefit of better lighting, and caused increased acoustic problems due to sound reverberation. Llinares et al. (2021c) found that wider classrooms resulted in lower student performance and lower emotional arousal. On the other hand, descriptive studies have found that "Fat L"-shaped classrooms, in which both legs are of nearly equal length and width, facilitate grouping among students to perform activities, with the result that learning is enhanced (Lippman, 2004). Other lines of research have examined how the presence and arrangement of furniture influence students' interactions (Baum, 2018; Park and Choi, 2014; Ramli et al., 2013; Wannarka and Ruhl, 2008) and experiences (Earthman, 2002; Fisher, 2001).

In general, these analyses examined design elements in isolation, very rarely in combination. However, to identify their relative importance, the different design elements should be analysed in combination. For example, if designers wished to change the design of a classroom, and for economic reasons could modify only one element, which would be selected? Which has the greatest impact on students' learning processes?

From a methodological viewpoint, this issue involves a fundamental difficulty, that is, how to modify and analyse individual design elements without changing the remaining elements; the use of physical spaces in this context is problematic because of the high cost of making modifications. Virtual Reality (VR) is an ideal low-cost alternative that allows experimenters to control variables (Latini, 2021). In this regard, Karakas and Yildiz (2020) in a systematic review found that VR is commonly used in subjective perception studies of architectural spaces as it offers simulated environments which appear similar to real environments. The validity of virtual environments has been demonstrated in experiments in which subjects exhibited similar physiological responses and behaviours in both VR and real-life scenarios (Armougum et al., 2019; Higuera-Trujillo et al., 2017; Marín-Morales et al., 2019); in addition, when similar behaviours were exhibited, the participants reported that the VR created a strong sense of presence (Heydarian et al., 2015). In the academic field, similarities in cognitive performance have been demonstrated in real and in VR-based classrooms (Kalantari et al., 2021). Coleman et al. (2019) demonstrated that working memory training undertaken in a controlled VR environment can subsequently be applied to improve memory function in real world environments. Furthermore, some authors have found that VR is an effective tool for measuring attention performance (Diaz-Orueta et al., 2013; Iriarte et al., 2016) and working memory (Matheis et al., 2007) in learning contexts (Rizzo et al., 2009; Areces et al., 2018). These methodological advances have made it possible to analyse the effects of space in learning contexts.

It is fundamental that educational spaces should be designed to enhance the cognitive processes involved in student learning. Among these processes, attention and memory should be highlighted, as they are the main neuropsychological functions that support learning (Bernabéu, 2017). In the academic context, classrooms are the main focus as their design characteristics have been shown to influence the performance of primary (Hathaway, 1995; Tanner, 2000), secondary/high school/senior (Shamaki, 2015) and university (Lizzio et al., 2002) students. However, it is important to recognise that learning is a complex cognitive process which is influenced not only by the physical environment in which it takes place, but also by external factors, such as student-instructor interactions (Lindblom-Ylänne et al., 2003) and the socio-cultural conditions of the environment (Eccles, 2005), and by internal factors, such as emotional states (Hascher, 2010).

Thus, account should be taken of the cognitive functions that teaching spaces aim to enhance. An exam may require higher memory performance, whereas a master's degree class might require more attention. It is, thus, increasingly common, to prompt desired behaviours, to base the design of spaces not only on measures of architectural design variables, but also on measurements taken of the responses of experimental participants (Bullinger et al., 2010; Mavros et al., 2021).

In most of the previously cited references, the subject's participation is limited to answering questions about his/her personal assessment of different environments (Nyrud et al., 2014). A subject's stated preference for a space is, without doubt, a metric that provides important information about his/her subjective and conscious perceptions (Baird et al., 1978), but this data must be complemented by other, objective metrics that address the cognitive processes that (s)he undergoes in the space, particularly in the context of classrooms. It is important to gather information about both types of variables because their effects do not always coincide. Previous research has shown there is a positive relationship between subjects' preferences for an environment and their performance (Cockerill and Miller, 1983; Shen et al., 2020) and calm mood (Costa et al., 2018). However, other research has suggested that mood is not affected by dominant preference (Lipson-Smith et al., 2021).

Moreover, the influence of design on human learning may not be equal for males and females. Each person has their own specific cognition and way of interacting with their environment. Research in this field has shown that males and females process the information, including interior design elements, they take in from the environment, in different ways (Picucci et al., 2011).

The objective of this study is to identify and analyse the relative impact of individual elements of classroom design (lighting, colour and geometry) on university students' (segmented by gender) cognitive performance (attention and memory), and preferences for different classroom designs.

2. Materials and methods

A laboratory experiment was carried out to achieve the objective. Four virtual classrooms were designed, three with different lighting, colour and geometry, and a control classroom. This allowed a comparison to be made between results obtained by subjects in cognitive tests in three modified environments and results obtained in a control classroom. The analysis of the results was carried out in three consecutive phases. First, the virtual simulations carried out were validated (Phase I). Measurements were then taken of the subjects' memory and attention performance and preference for each of the virtual environments (Phase II). Finally, the differences found were quantified and compared based on gender (Phase III). The experimental procedure was conducted in compliance with the Declaration of Helsinki, and was approved by the Review Board (Project P1_25_07_18) of the Polytechnic University of Valencia. Figure 1 shows the general experimental outline.

2.1. Sample

The experimental sample was made up 200 subjects, gender balanced (100 male and 100 female), with an average age of 23.34 years (standard deviation, $\sigma = 3.73$). All fulfilled the conditions of having read and signed an informed consent document, being students, and not having visual acuity and field problems or, if they had, having the corresponding optical correction using contact lenses (it was not possible to employ subjects wearing spectacles as this inhibits their ability to use VR devices). In addition, their colour vision was tested using the Farnsworth–Munsell Dichotomous D-15 Test. All subjects viewed four virtual classrooms, a control classroom, a classroom with modified lighting, a classroom with modified colour and a classroom with modified geometry. The order of the viewing of the four groups of classrooms followed complete counterbalancing. The experimental design ensured that the three groups of modified design elements (lighting, colour and geometry) were presented randomly and that all modifications were viewed a similar number of times (difference of less than two viewings). In all the virtual classrooms, the subjects had to perform, in the following order, memory tasks and attention tasks, and then to state their preferred virtual environment. At the end of each experiment, the level of the subjects' sense of presence was evaluated. The gender of the subjects (male and female) and the virtual classroom types (control, lighting, colour and geometry) combined to create eight groups of students.

2.2. Stimuli

The stimuli were virtual reality classrooms. The control classroom was a virtual replica of a room in the Polytechnic University of Valencia, chosen because it is representative of this type of space in Spain. The classroom had the following physical characteristics: neutral white wall colour (N5 in the Munsell colour system), height, width and length typical of classrooms in the university (3.80 m × 8.40 m × 16.50 m) and commonly used artificial lighting (colour temperature of 4000 K, 300 lx of illuminance, and direct flow). The three groups of modifications were based on variations (from the control classroom) of the parameters of the design elements: interior artificial lighting (colour temperature and illuminance); wall colour (saturation and hue); and geometry (height—the clear height from floor to ceiling, and width—the distance between the longitudinal walls). The modification values chosen were based on standard construction criteria (Fig. 2). For lighting, the most common bulbs on the market

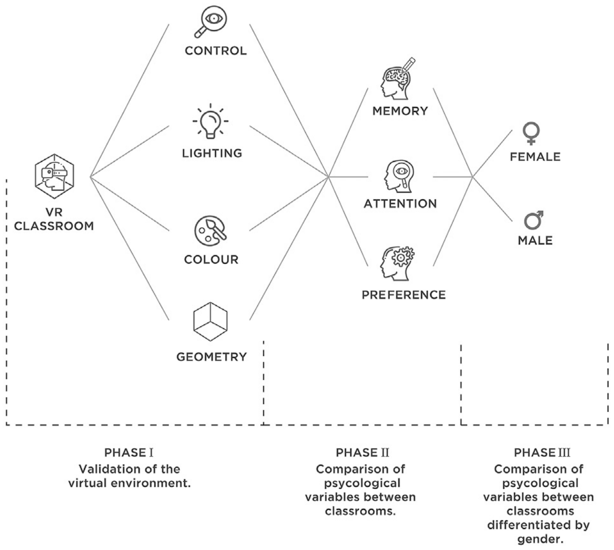


Fig. 1 General methodological schema.

were chosen. For colour, the choice was to use 10 different shades evenly distributed on the Munsell colour wheel, with two saturations always separated by 6 chroma units, and an intermediate constant value of 5 units. For geometry, the choice was to use one of the modules/units frequently employed in the manufacture of flooring and false ceiling parts.

To ensure that other factors had no effect, the position and direction of the lighting, the furniture and its distribution, and other materials and finishes were maintained, as was the location of the subject within the virtual reality classroom (Fig. 3).

2.3. Virtual simulation set-ups

The virtual classrooms were created through a modelling and rendering process. The modelling was carried out using Rhinoceros (v.5.0), and the rendering using V-Ray Renderer (v.3.3), running on Autodesk 3ds Max (v.2014). The renders were configured as 360° panoramas, saved in a JPG format with a resolution of 8000 × 4000 pixels. As aforementioned, the subject's location (a chair in the centre of the second row of desks) remained constant.

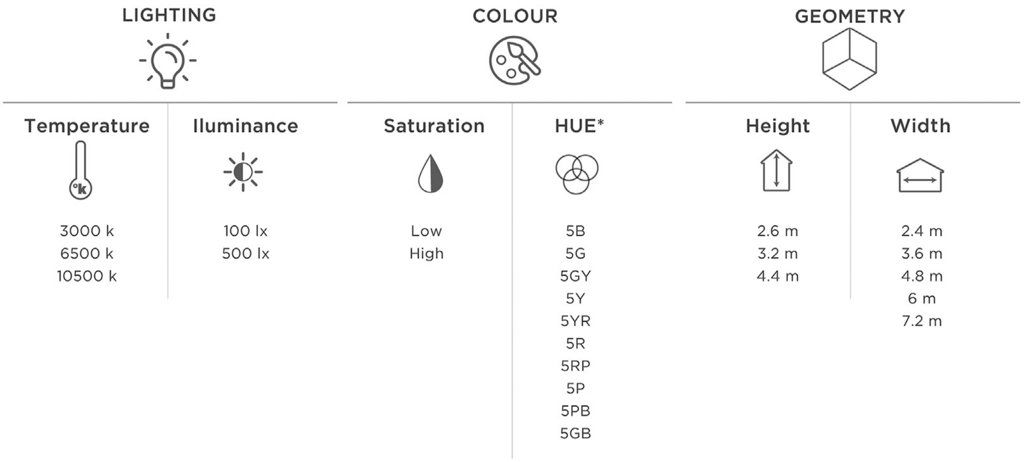
The renders were presented using Unity3D software (v5.6), which allowed them to be viewed in an immersive way. The viewing device used was the HTC Vive head-mounted display (some details to note about this device are: total resolution 2160 × 1200 pixels, 110° field of view and 90 Hz refresh rate). The HTC Vive device was connected to a high-performance computer (CPU, i9-10900 K, RAM 64 GB, GPU RTX3080), which allowed the subjects to smoothly view the virtual classrooms. To maximise the subjects' immersion, the laboratory lights were turned off, and the room was soundproofed against external noise.

2.4. Procedure

The experiment was conducted in a laboratory, always in the same time slot. The procedure consisted of 6 phases (Fig. 4).

The total duration of the procedure was 30 min.

- In the 1st phase (preparation), the subject was welcomed into the laboratory and the room was prepared for the experiment; instructions were provided to the subjects; the colour vision status of each subject was assessed through the Farnsworth—Munsell Dichotomous D-15 test. Duration: around 5 min.
- In the 2nd phase (habituation) the subjects viewed a VR space/room to get them accustomed to the system. This space/room differed "physically" from the four stimuli classrooms used in the experiment: it was of simple design and neutral colours and lighting and had no furniture nor identifying elements. Duration: until the subject considered that (s) he was accustomed to the VR system.
- The 3rd phase (attention and memory test) began with the issuing of instructions followed by a 60-s break (during which the subjects did not view any images). Thereafter, the subjects viewed, randomly, for 60 s, one of the virtual classrooms: the control, the lighting-modified, the geometry-modified or the colour-modified classroom. While the subjects were immersed



LIGHTING		COLOUR		GEOMETRY	
Temperature	Iluminance	Saturation	HUE*	Height	Width
3000 k 6500 k 10500 k	100 lx 500 lx	Low High	5B 5G 5GY 5Y 5YR 5R 5RP 5P 5PB 5GB	2.6 m 3.2 m 4.4 m	2.4 m 3.6 m 4.8 m 6 m 7.2 m

Fig. 2 Schema of the parameters analysed: lighting, colour and geometry.

Fig. 3 Set of classrooms visualised as stimuli. The left, middle and right columns show the control classroom characteristics with the modifications corresponding to all possible combinations of the studied parameters of lighting element, colour and geometry, respectively.

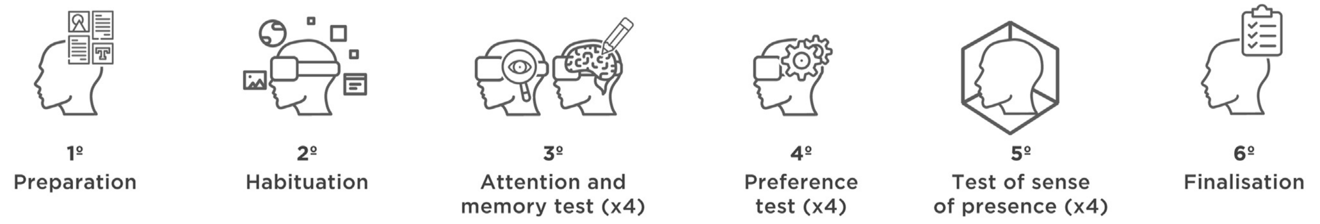


Fig. 4 Experimental procedure: The 6 consecutive steps taken in the research process. The 2nd, 3rd and 4th phases were undertaken using virtual reality.

in the virtual classrooms, specific tests measured their levels of memory and attention. To ensure the results did not suffer from response desirability the experimenters explained to the subjects that there were no right or wrong answers. Duration: approximately 15 min.

- In the 4th phase (preference test) the subject was immersed in the same classroom, but in this case a rating scale of -4 to 4 was displayed on the classroom's blackboard. Using this scale, the subjects responded to a questionnaire about the classroom in general, and its architectural elements. This phase gathered the subjects' environmental preferences. Duration: about 2 min.
- In the 5th phase (test of sense of presence) the subjects removed the HMDs and responded to a SUS questionnaire (Slater et al., 1994) that assessed their level of sense presence in the virtual classrooms. Duration: about 2 min.
- In the 6th phase (finalisation) the subjects completed a demographic questionnaire, and the experimental session ended. Duration: about 4 min.

2.5. Metrics

Test of sense of presence. A SUS questionnaire was used to quantify the level of sense of presence of the subjects (Slater et al., 1994). This questionnaire, which employs a 6-point Likert scale (1–7), is a measure widely used to quantify and understand subjects' degree of sense of presence in virtual environments. Low scores (closer to 0) indicate that subjects perceive the environments as artificial, while high scores (closer to the maximum of 42, that is, 7 points × 6 Items) indicate they perceive a high sense of presence in the VR environment. Based on the results of previous research, it was estimated that scores of 24 or above represented an optimal sense of presence (Slater and Steed, 2000).

Attention test. The subjects' attention performance was measured in a psychological task in which they had to react as quickly as possible to specific auditory stimuli. The subjects listened to 4 different sounds/stimuli, having been previously told that only one was the target stimulus, and that the remaining three were distractors. The subjects then listened to 40 sounds, of which 8 were target stimuli, randomly presented. They were asked to click a mouse only when they heard the target stimuli. This process was carried out 3 times, meaning the subjects listened to 24 target sounds and 96 distractors. The task is similar to those undertaken in continuous auditory performance tests (Seidman et al., 1998) which calculate reaction times. The presentation and randomisation of the sounds in the attention test were specifically developed for this experiment. This overall process provided the sustained attention metric.

Memory test. The subjects' memory performance was measured in a psychological task in which they had to memorise a list of words broadcast by a recording device. Following Alonso et al. (2004), they were presented with 3 lists of 15 words each, randomised from a total of 15 lists. The lists were presented at 15 s intervals. Immediately after the presentation of each list, the subjects were asked to repeat the words they remembered, in any order. To avoid collecting erroneous data based on any lapses made by the researchers, the subjects' responses were recorded. The number of total correct answers was calculated following the DRM paradigm (Beato and Díez, 2001). The words were presented by Loquendo TTS 7, reproduced through Windows Media Player. Thus, the working memory metric was obtained.

Environmental preferences. To measure their level of classroom preference the subjects were posed a question, specifically designed for the present study, about their perceptions of the environment they had viewed. The subjects were asked to respond based on a Likert scale of -4 to 4 presented in the virtual classroom, where it was viewed in real time. They were asked to "rate from -4 to 4 the extent to which you agree with the following statement: in general, I like this classroom". Choosing -4 indicated the subjects completely disagreed with the statement, and $+4$ indicated total agreement with the statement. Thus, their levels of personal preference for, and their degree of "I like" of, the classrooms were assessed, and the preference metric of the environment was obtained.

2.6. Statistical analysis

The data were analysed using SPSS v. 26.0. The normality of the data was checked by the Kolmogorov-Smirnov test, with the Lilliefors significance correction. The test showed that the data were normally distributed. On this basis, an analysis of variance (ANOVA) was applied. In addition, a descriptive analysis of means was performed to validate the stimuli. All p values < 0.05 were considered statistically significant. According to Lakens (2013), the effect sizes were reported with partial eta squared (η_p^2). Table 1 shows the analyses performed to address the relevant issues.

3. Results

The effects of the design were analysed at the level of each element (the changes in all three parameters, lighting, colour and geometry, being grouped together). This provided three groups, lighting, colour and geometry (in addition to the control classroom). Their means were normalised so that they could be represented on the same axis. The statistical analysis of the data produced the following results.

3.1. Phase I: analysis of sense of presence

Measures were made of the subjects' average levels of sense of presence for the four classrooms. The results showed values higher than 28, with the mean level of sense of presence in females being higher than in males (31.98 versus 29.06). Based on the results obtained by Slater and Steed (2000), who used the SUS questionnaire with the SUS-total metric, it is reasonable to conclude that the levels of sense of presence obtained were satisfactory. Fig. 5 depicts the average levels of sense of presence for the four scenarios.

3.2. Phase II: analysis of the impact of design elements on the variables students' memory, attention and preferences

Following the validation of the VR environment, statistical techniques were used to compare the responses to the different design elements, lighting, colour and geometry, with responses to the control room. Given the normality of the variables, an ANOVA test was applied. The results are shown in Fig. 6.

- Working memory metric. The control classroom returned the poorest results. Modified lighting significantly improved the results ($F_{(1,682)} = 6.304$, $p = 0.012$, $\eta_p^2 = 0.009$). While geometry and colour modifications did improve performance in the memory test, the results were not significant ($p > 0.05$).
- Sustained attention metric. Again, the worst results were obtained in the control classroom, where reaction times were the longest, thus attention paid was the poorest. Reaction time was significantly reduced, that is, improved, by classroom interventions in lighting ($F_{(1,613)} = 5.230$, $p = 0.021$, $\eta_p^2 = 0.009$), colour ($F_{(1,562)} = 3.434$, $p = 0.027$, $\eta_p^2 = 0.006$) and geometry ($F_{(1,835)} = 4.898$, $p = 0.023$, $\eta_p^2 = 0.006$), which demonstrates the sensitivity of the cognitive function attention to classroom design.
- Environmental preference metric. Again, the worst results were obtained in the control classroom. As with memory, interventions in colour and geometry did not significantly improve the results ($p > 0.05$). Lighting modifications, however, significantly ($F_{(1,679)} = 16.68$, $p < 0$, $\eta_p^2 = 0.024$) improved the results.

Table 1 Statistical treatment. *In all cases, the variables analysed were: memory (memory hits), attention (speed of correct attention measure responses) and preference (subjective classroom rating score). The means were normalised so that they could be represented on the same axis.

Phase	Analysis	Statistical treatment	Question to answer
Phase I: Analysis of sense of presence	Examination of the level of sense of presence in the different VR scenarios	Descriptive analysis (mean and standard deviations)	Are the stimuli presented in the VR valid?
* Phase II: Analysis of the impact of the design elements on the students' attention, memory and preferences	Comparative analysis of the levels of memory, attention and preference between the control classroom and the classrooms modified in lighting, colour and geometry.	ANOVA analysis (normally distributed data) for memory, attention and preference for the different design elements.	Which design element (lighting, colour or geometry) had the most impact on the students' memory, attention and preferences?
* Phase III: Analysis of the impact of the design elements on the students' attention, memory and preferences, as a function of gender	Comparative analysis of the level of students' memory, attention and preference between the control classroom and the classrooms modified in lighting, colour and geometry, as a function of gender.	ANOVA analysis (normally distributed data) for memory, attention and preference for the different design elements, as a function of gender.	Which design element (lighting, colour or geometry) had the most impact on the students' memory, attention and preferences, as a function of gender?

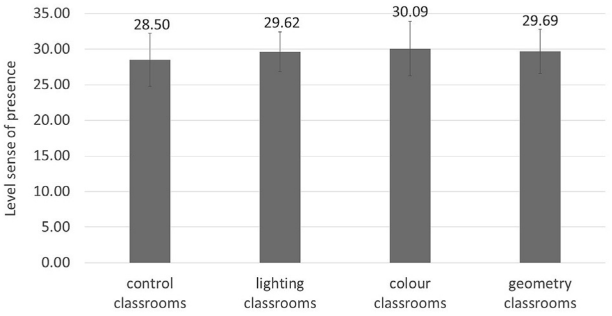


Fig. 5 Average level of sense of presence in each simulated classroom type.

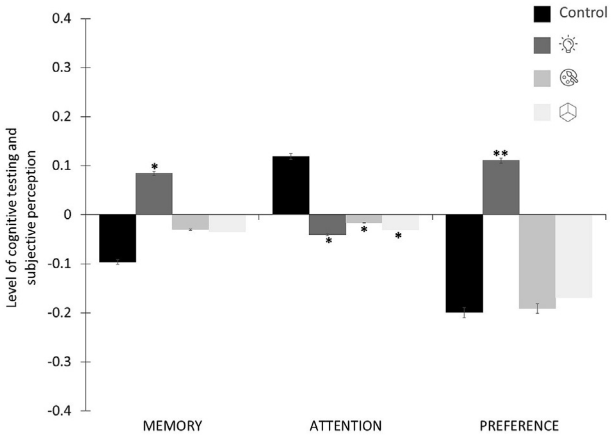


Fig. 6 Relationship between subjects' psychological metrics and classroom design elements. The asterisks indicate significance levels (*p < 0.05, **p < 0.01).

Therefore, in general, lighting was shown to be the design element with the most influence, as it affects not only preference, but also the cognitive functions attention and memory. Nonetheless, attention must be drawn to the effect of design on the sustained attention metric, which was shown to be the most sensitive to design variations.

3.3. Phase III: analysis of the impact of design elements on the variables students' memory, attention and preferences, as a function of gender

To analyse differences due to gender, the same analysis as carried out in Phase II was conducted, but this time segmenting the responses between males and females. Figure 7 shows the results obtained.

- Working memory metric. Lighting improved the test results, as was the case in Phase II, but the improvement was only significant ($F_{(1,310)} = 6.06$, $p = 0.014$, $\eta_p^2 = 0.019$) in the male group.
- Sustained attention metric. While design interventions did improve results in the male group, the enhancements were not significant ($p > 0.05$). However, for the female group, changes in lighting and colour significantly reduced reaction times ($F_{(1,301)} = 5.507$, $p = 0.020$, $\eta_p^2 = 0.018$; $F_{(1,259)} = 4.254$, $p = 0.040$, $\eta_p^2 = 0.016$, respectively). While geometry was not shown to be significant, it was close to significant ($p < 0.075$) for both genders.
- Environmental preference metric. For both genders, lighting significantly improved ($F_{(1,310)} = 5.085$, $p = 0.025$, $\eta_p^2 = 0.016$ for males; $F_{(1,325)} = 12.379$, $p < 0$, $\eta_p^2 = 0.037$ for females) the ratings.

In general, the results showed that gender must be taken into account in this type of analysis, given that the differences between the groups were significant. In detail, it was observed that only lighting had a significant effect on environmental preferences for both groups, and that it affected memory among males and attention among females. The same was the case with attention, which was seen to have the greatest effects among the design changes, but only for females. This analysis allows us, therefore, to present the results in a specific fashion.

4. Discussion

The present study analyses the relative impact that lighting, colour and geometry have on the memory, attention and preferences of university students, segmented by gender. The fundamental contributions of the study are the comparison of the effects of the different design elements and its segmentation of the results by gender.

Following this line of argument, the discussion of the results is now presented in two main sections: First, the effects of each of the design elements on the psychological variables and, second, the mediating effects of gender on these relationships. Finally, we discuss the limitations of the study.

As to the relative impact of changes to the design elements, the results showed that lighting (i.e., changes in illuminance and colour temperature) had the greatest influence on preference and performance in attention and memory tests. These results are consistent with previous studies that analysed the influence of lighting on cognitive performance (Hygge and Knez, 2001; Keis et al., 2014; Knez and Kers, 2000). The relative importance of the effect of lighting on learning in comparison to other design elements may be related to the direct involvement of light in many internal biological processes, such as circadian rhythms (Rea et al., 2002), and levels of cortisol, a hormone related to activation and improvement in cognitive performance (Gabel et al., 2013), and to psychological processes, such as attention (Studer et al., 2019). In any case, that light levels determine, to some extent, activity in human beings, suggests that lighting-related nuances are easier to perceive, which would explain the differences between the levels of stated preferences for classrooms with different lighting (Huang et al., 2020). Segmented by gender, it was observed that lighting changes affected males' memories and females' attention levels. Previous studies have shown that males and females respond differently to colour temperature changes (Lu et al., 2019).

Colour was the next most influential element. Colour changes in the classrooms (different hues and saturations) significantly affected attention levels among the females. Earlier VR-based research also established the existence

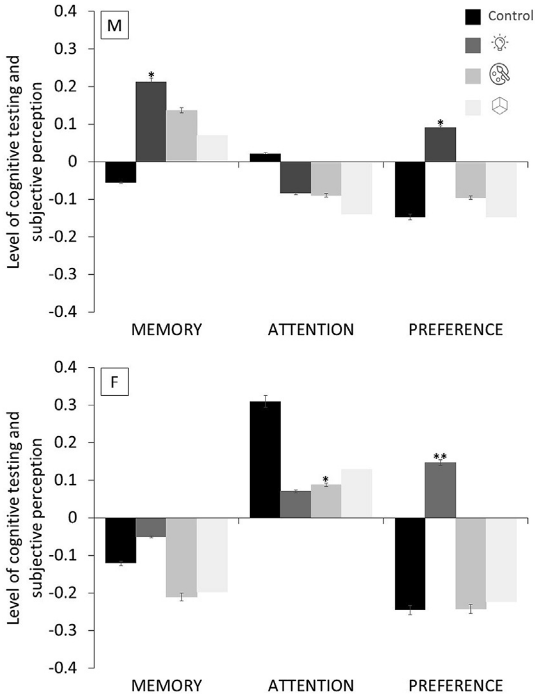


Fig. 7 Relationships between the subjects' psychological variables (M: male and F: female) and the design elements of the classrooms. The asterisks indicate the significance levels (*$p < 0.05$, **$p < 0.01$).

of significant gender-based differences; specifically, females have been seen to make more errors than males in single-choice tests when using computer screens with yellow backgrounds, but fewer mistakes when using screens with orange backgrounds (Xia et al., 2022). In this sense, females are more able to distinguish darker colours than are males, especially at ages characterised by oestrogen hormonal changes (Correa et al., 2007). These gender-based differences in the perception of (Hurlbert and Ling, 2012), and preference for (Jalil et al., 2013), colours have been extensively examined in various settings, with different experimental aims (Funk and Ndubisi, 2006; Huang et al., 2019), which supports the universality of the phenomenon.

Finally, geometry (classroom ceiling height/width) was shown to be the least influential element in students' cognition. In general, geometry has been little analysed in the scientific literature, although previous research has found a link between classroom width and cognitive performance (Llinares et al., 2021c). In the present study, significant improvements in the reaction times in the attention test were observed when interventions were made in the height/width of the classrooms. A very near to significant gender-based difference was also observed in the attention test.

In short, the results showed, as other authors have observed (Barrett et al., 2015), that a direct relationship exists between the design elements lighting, colour and geometry and students' learning and preferences. The results also showed that, of the three metrics examined (working memory, sustained attention and environmental preferences), sustained attention was the most sensitive to classroom design interventions. An explanation for this result may be that the simultaneous activation of external attention (to the VR-based stimuli) and internal attention (to the tasks) overwhelmed the overall system. While both attention types have distinct neural networks, they share connections that can, based on certain circumstances, interfere negatively with their operations (Maillet et al., 2019). Thus, the environment could be exerting a distracting function on attention (Rodrigues and Pandeirada, 2015). In addition, while it was shown that all changes to the design elements of the environment affected attention levels, preference was particularly sensitive to changes in lighting. That changes in lighting levels are particularly perceptible may be due to an adaptation and survival mechanism. Lighting has been shown to have an important role in human physiology (Pilorz et al., 2018) and, in particular, it is very involved in the operation of biological mechanisms, such as circadian rhythms (Tähkämö et al., 2019).

The results showed that design elements produce significant gender-based differences, as found in previous studies (Lu et al., 2019; Nolé et al., 2021; Xia et al., 2022). This is consistent with the notion that spatial orientation in males and females develops in different ways (Bosco et al., 2004; Coluccia and Louse, 2004), which implies that males and females perceive space differently.

The results may also have been affected by psychological factors, such as emotional state, which has been shown to influence cognitive processing (Hascher, 2010). It should be noted, also, that the VR scenarios could be exerting an effect on the results—it is known that males and females use technologies in different ways (Miola et al., 2021). Thus, future research should address these possible limitations by complementing the analysis, for example, of sense of presence, by using spatial orientation tests (segmenting by gender) in VR environments (Allahyar and Hunt, 2003), and by assessing the emotions generated by the spaces.

Finally, focusing the research on a classroom with a specific design (layout, furniture, ...) may be a limitation. However, it was considered important to modify only the variables under study, keeping the rest constant. For this reason, a control classroom that could accommodate the proposed changes, and that was representative of Spanish universities, was chosen. Future work might replicate the analysis in a classroom with other characteristics, in terms of layout/furniture.

5. Conclusions

This study compares the effects that classroom lighting, colour and geometry exert on the attention, memory and preferences of university students, segmenting by gender. The analysis identified that design elements affect individual variables in distinct ways and have different effects on females and males. Specifically, lighting was shown to be the most influential design element; it affected males' memories, females' attention and the preferences of both. Colour was the next most influential design element; it produced a notable effect on females' attention. Geometry was shown to have the least impact on students' cognition. Finally, it is important to highlight the sensitivity of attention to overall classroom design. The evidence presented in this study has considerable implications for education and educators; based on it, practical modifications can be proposed to improve classroom design.

Existing classrooms could be modified to increase students' performances in specific situations (e.g., increased recall at exam time). Lighting modifications should be prioritised because they most affect learning, and can be made without undertaking construction works (they involve only changing light bulbs), and the currently available lighting solutions would allow immediate modifications to be made to the parameters studied (illuminance and colour temperature). The findings of the present study allow us to propose new principles for the design of educational environments. Putting these principles into effect might enhance teachers' and students' perceptions of the value of classroom design. This, in turn, may prompt them to become more involved in the design of interior projects. These results may be of interest to architects, interior designers and engineers who wish to create classrooms that satisfy the psychological needs of their students.

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.

Acknowledgments

Grant BIA 2017-86157-R was funded by MCIN/AEI/10.13039/501100011033 and by ERDF, "A way of making Europe". The first author is supported by the Ministry of Science, Innovation and Universities of Spain (FPU19/03531). The second author (postdoctoral fellow "Margarita Salas") is supported by funding from the Spanish Ministry of Universities and by the European Union NextGenerationEU.

References

Ahrentzen, S., Evans, G.W., 1984. Distraction, privacy, and classroom design. Environ. Behav. 16 (4), 437—454. https://doi.org/10.1177/0013916584164002.

Allahyar, M., Hunt, E., 2003. The assessment of spatial orientation using virtual reality techniques. Int. J. Test. 3 (3), 263—275. https://doi.org/10.1207/S15327574IJT0303_5.

Areces, D., Dockrell, J., García, T., González-Castro, P., Rodríguez, C., 2018. Analysis of cognitive and attentional profiles in children with and without ADHD using an innovative virtual reality tool. PLoS One 13 (8), e0201039. https://doi.org/10.1371/journal.pone.0201039.

Armougum, A., Orriols, E., Gaston-Bellegarde, A., Joie-La Marle, C., Piolino, P., 2019. Virtual reality: a new method to investigate cognitive load during navigation. J. Environ. Psychol. 65, 101338. https://doi.org/10.1016/j.jenvp.2019.101338.

Alonso, M.Á., Fernández, Á., Díez, E., Beato, M.S., 2004. Índices de producción de falso recuerdo y falso reconocimiento para 55 listas de palabras en castellano. Psicothema 16, 357—362.

Baird, J.C., Cassidy, B., Kurr, J., 1978. Room preference as a function of architectural features and user activities. J. Appl. Psychol. 63 (6), 719. https://doi.org/10.1037/0021-9010.63.6.719.

Barrett, P., Davies, F., Zhang, Y., Barrett, L., 2015. The impact of classroom design on pupils' learning: final results of a holistic, multi-level analysis. Build. Environ. 89, 118—133. https://doi.org/10.1016/j.buildenv.2015.02.013.

Baum, E.J., 2018. Learning space design and classroom behavior. International Journal of Learning. Teaching and Educational Research 17 (9), 34—54. https://doi.org/10.26803/ijlter.17.9.3.

Beato, M.S., Díez, E., 2001. False recognition production indexes in Spanish for 60 DRM lists with three critical words. Behav. Res. Methods 43, 499—507.

Bernabéu, E., 2017. Attention and Memory: critical processes for learning. Applications for educational environments. ReiDoCrea 6 (2), 16—23. https://doi.org/10.30827/Digibug.47141.

Bernardo, F., Loupa-Ramos, I., Matos Silva, C., Manzo, M., 2021. The restorative effect of the presence of greenery on the classroom in children's cognitive performance. Sustainability 13 (6), 3488. https://doi.org/10.3390/su13063488.

Bosco, A., Longoni, A.M., Vecchi, T., 2004. Gender effects in spatial orientation: cognitive profiles and mental strategies. Appl. Cognit. Psychol.: The Official Journal of the Society for Applied Research in Memory and Cognition 18 (5), 519—532. https://doi.org/10.1002/acp.1000.

Bullinger, H.J., Bauer, W., Wenzel, G., Blach, R., 2010. Towards user centred design (UCD) in architecture based on immersive virtual environments. Comput. Ind. 61 (4), 372—379. https://doi.org/10.1016/j.compind.2009.12.003.

Cockerill, I.M., Miller, B.P., 1983. Children's colour preferences and motor skill performance with variation in environmental colour. Percept. Mot. Skills 56 (3), 845—846. https://doi.org/10.2466/pms.1983.56.3.8.

Coleman, B., Marion, S., Rizzo, A., Turnbull, J., Nolty, A., 2019. Virtual reality assessment of classroom—related attention: an ecologically relevant approach to evaluating the effectiveness of working memory training. Front. Psychol. 10, 1851. https://doi.org/10.3389/fpsyg.2019.01851.

Coluccia, E., Louse, G., 2004. Gender differences in spatial orientation: a review. J. Environ. Psychol. 24 (3), 329—340. https://doi.org/10.1016/j.jenvp.2004.08.006.

Correa, V., Estupiñán, L., García, Z., Giménez, O., Prada, L.F., Rojas, A., Rojas, S., Cristancho, E., 2007. Perception of the visible spectrum: differences among gender and age. Revista Med 15 (1), 2.

Costa, M., Frumento, S., Nese, M., Predieri, I., 2018. Interior color and psychological functioning in a university residence hall. Front. Psychol. 9, 1580. https://doi.org/10.3389/fpsyg.2018.01580.

Cubukcu, E., Kahraman, I., 2008. Hue, saturation, lightness, and building exterior preference: an empirical study in Turkey comparing architects' and nonarchitects' evaluative and cognitive judgments. Color Res. Appl. 33 (5), 395—405. https://doi.org/10.1002/col.20436.

Diaz-Orueta, U., Garcia-López, C., Crespo-Eguilaz, N., Sánchez-Carpintero, R., Climent, G., Narbona, J., 2013. AULA virtual reality test as an attention measure: convergent validity with Conners' Continuous Performance Test. Child Neuropsychol. 20, 328—342. https://doi.org/10.1080/09297049.2013.792332.

Earthman, G.I., 2002. School Facility Conditions and Student Academic Achievement. 's Institute for Democracy, Education, UCLA (and Access).

Earthman, G.I., 2004. Prioritization of 31 criteria for school building adequacy: American Civil Liberties Union Foundation of Maryland 10, 4—8. Accessed online on.

Eccles, J.S., 2005. Influences of parents' education on their children's educational attainments: the role of parent and child perceptions. Lond. Rev. Educ. 3 (3), 191—204. https://doi.org/10.1080/14748460500372309.

Fisher, K., 2001. Building Better Outcomes: the Impact of School Infrastructure on Student Outcomes and Behavior. Schooling Issues Digest.

Funk, D., Ndubisi, N.O., 2006. Colour and product choice: a study of gender roles. Manag. Res. News 29 (1/2), 41—52. https://doi.org/10.1108/01409170610645439.

Gabel, V., Maire, M., Reichert, C.F., Chellappa, S.L., Schmidt, C., Hommes, V., Viola, A.U., Cajochen, C., 2013. Effects of artificial dawn and morning blue light on daytime cognitive performance, well-being, cortisol and melatonin levels. Chronobiol. Int. 30 (8), 988—997. https://doi.org/10.3109/07420528.2013.793196.

Gao, X.P., Xin, J.H., 2006. Investigation of human's emotional responses on colors. Color Res. Appl. 31 (5), 411—417. https://doi.org/10.1002/col.20246.

Hascher, T., 2010. Learning and emotion: perspectives for theory and research. Eur. Educ. Res. J. 9 (1), 13—28. https://doi.org/10.2304/eerj.2010.9.1.13.

Hathaway, W.E., 1995. Effects of school lighting on physical development and school performance. J. Educ. Res. 88 (4), 228—242. https://doi.org/10.1080/00220671.1995.9941304.

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

Higuera-Trujillo, J.L., Maldonado, J.L.T., Millán, C.L., 2017. Psychological and physiological human responses to simulated and real environments: a comparison between Photographs, 360 Panoramas, and Virtual Reality. Appl. Ergon. 65, 398—409. https://doi.org/10.1016/j.apergo.2017.05.006.

Huang, Z., Liu, Q., Liu, Y., Pointer, M., Bodrogi, P., Khanh, T.Q., Liu, A., 2020. Gender difference in colour preference of lighting: a pilot study. Light Eng 28 (4), 111—122.

Huang, Z., Liu, Q., Liu, Y., Pointer, M.R., Luo, M.R., Wang, Q., Wu, B., 2019. Best lighting for jeans, part 1: optimising colour preference and colour discrimination with multiple correlated colour temperatures. Light. Res. Technol. 51 (8), 1208—1223. https://doi.org/10.1177/1477153518816125.

Hurlbert, A., Ling, Y., 2012. Understanding colour perception and preference. In: Best, J. (Ed.), Colour Design. Theories and Applications. Woodhead Publishing, Sawston, pp. 129—157.

Hygge, S., Knez, I., 2001. Effects of noise, heat and indoor lighting on cognitive performance and self-reported affect. J. Environ. Psychol. 21 (3), 291—299. https://doi.org/10.1006/jevp.2001.0222.

Iriarte, Y., Diaz-Orueta, U., Cueto, E., Irazustabarrena, P., Banterla, F., Climent, G., 2016. AULA—advanced virtual reality tool for the assessment of attention: normative study in Spain. J. Atten. Disord. 20, 542—568.

Jalil, N.A., Yunus, R.M., Said, N.S., 2013. Students' colour perception and preference: an empirical analysis of its relationship. Procedia-Social and Behavioral Sciences 90, 575—582. https://doi.org/10.1016/j.sbspro.2013.07.128.

Kalantari, S., Rounds, J.D., Kan, J., Tripathi, V., Cruz-Garza, J.G., 2021. Comparing physiological responses during cognitive tests in virtual environments vs. in identical real-world environments. Sci. Rep. 11 (1), 1—14. https://doi.org/10.1038/s41598-021-89297-y.

Karakas, T., Yildiz, D., 2020. Exploring the influence of the built environment on human experience through a neuroscience approach: a systematic review. Frontiers of Architectural Research 9 (1), 236—247. https://doi.org/10.1016/j.foar.2019.10.005.

Keis, O., Helbig, H., Streb, J., Hille, K., 2014. Influence of blue-enriched classroom lighting on students' cognitive performance. Trends in Neuroscience and Education 3 (3—4), 86—92. https://doi.org/10.1016/j.tine.2014.09.001.

Knez, I., Kers, C., 2000. Effects of indoor lighting, gender, and age on mood and cognitive performance. Environ. Behav. 32 (6), 817—831. https://doi.org/10.1177/0013916500326005.

Kwallek, N., Lewis, C.M., Lin-Hsiao, J.W.D., Woodson, H., 1996. Effects of nine monochromatic office interior colors on clerical tasks and worker mood. Color Res. Appl. 21 (6), 448—458.

Lakens, D., 2013. Calculating and reporting effect sizes to facilitate cumulative science: a practical primer for t-tests and ANOVAs. Front. Psychol. 4, 863. https://doi.org/10.3389/fpsyg.2013.00863.

Latini, A., Di Giuseppe, E., D'Orazio, M., Di Perna, C., 2021. Exploring the use of immersive virtual reality to assess occupants' productivity and comfort in workplaces: An experimental study on the role of walls colour. Energy and Buildings 253, 111508. https://doi.org/10.1016/j.enbuild.2021.111508.

Lindblom-Ylänne, S., Pihlajamäki, H., Kotkas, T., 2003. What makes a student group successful? Student-student and student-teacher interaction in a problem-based learning environment. Learn. Environ. Res. 6 (1), 59—76. https://doi.org/10.1023/A:1022963826128.

Llinares, C., Castilla, N., Higuera-Trujillo, J.L., 2021a. Do attention and memory tasks require the same lighting? A study in university classrooms. Sustainability 13 (15), 8374. https://doi.org/10.3390/su13158374.

Llinares, C., Higuera-Trujillo, J.L., Montañana i Aviñó, A., Torres, J., entieri, C., 2021c. The influence of classroom width on attention and memory: virtual-reality-based task performance and neurophysiological effects. Build. Res. Inf. 49 (7), 813—826. https://doi.org/10.1080/09613218.2021.1899798.

Llinares, C., Higuera-Trujillo, J.L., Serra, J., 2021b. Cold and warm coloured classrooms. Effects on students' attention and memory measured through psychological and neurophysiological responses. Build. Environ. 196, 107726. https://doi.org/10.1016/j.buildenv.2021.107726.

Lippman, P.C., 2004. The L-Shaped Classroom: A Pattern for Promoting Learning. DesignShare (NJ1). https://eric.ed.gov/?id=ED497662.

Lipson-Smith, R., Bernhardt, J., Zamuner, E., Churilov, L., Busietta, N., Moratti, D., 2021. Exploring colour in context using Virtual Reality: does a room change how you feel? Virtual Real. 25 (3), 631—645. https://doi.org/10.1007/s10055-020-00479-x.

Lizzio, A., Wilson, K., Simons, R., 2002. University students' perceptions of the learning environment and academic outcomes: implications for theory and practice. Stud. High Educ. 27 (1), 27—52. https://doi.org/10.1080/03075070120099359.

Lu, Y., Li, W., Xu, W., Lin, Y., 2019. Impacts of LED dynamic white lighting on atmosphere perception. Light. Res. Technol. 51 (8), 1143—1158. https://doi.org/10.1177/1477153518823833.

Maillet, D., Beaty, R.E., Kucyi, A., Schacter, D.L., 2019. Large-scale network interactions involved in dividing attention between the external environment and internal thoughts to pursue two distinct goals. Neuroimage 197, 49—59. https://doi.org/10.1016/j.neuroimage.2019.04.054.

Marchand, G.C., Nardi, N.M., Reynolds, D., Pamoukov, S., 2014. The impact of the classroom built environment on student perceptions and learning. J. Environ. Psychol. 40, 187—197. https://doi.org/10.1016/j.jenvp.2014.06.009.

Marín-Morales, J., Higuera-Trujillo, J.L., Greco, A., Guixeres, J., Llinares, C., Gentili, C., Scilingo, E.P., Alcañiz, M., Valenza, G., 2019. Real vs. immersive-virtual emotional experience: analysis of psycho-physiological patterns in a free exploration of an art museum. PLoS One 14 (10), e0223881. https://doi.org/10.1371/journal.pone.0223881.

Matheis, R.J., Schultheis, M.T., Tiersky, L.A., DeLuca, J., Millis, S.R., Rizzo, A., 2007. Is learning and memory different in a virtual environment? Clin. Neuropsychol. 21, 143—161. https://doi.org/10.1080/13854040601100668.

Mavros, P., Conroy Dalton, R., Kuliga, S., Gath Morad, M., Robson, S., Hölscher, C., 2021. Architectural cognition cards: a card-based method for introducing spatial cognition research and user-centred thinking into the design process. Architect. Sci. Rev. 1—18. https://doi.org/10.1080/00038628.2021.2008299.

Mills, P.R., Tomkins, S.C., Schlangen, L.J., 2007. The effect of high correlated colour temperature office lighting on employee wellbeing and work performance. J. Circadian Rhythms 5 (1), 1—9. https://doi.org/10.1186/1740-3391-5-2.

Miola, L., Meneghetti, C., Toffalini, E., Pazzaglia, F., 2021. Environmental learning in a virtual environment: do gender, spatial self-efficacy, and visuospatial abilities matter? J. Environ. Psychol. 78, 101704. https://doi.org/10.1016/j.jenvp.2021.101704.

Nolé, M.L., Higuera-Trujillo, J.L., Llinares, C., 2021. Effects of classroom design on the memory of university students: from a gender perspective. Int. J. Environ. Res. Publ. Health 18 (17), 9391. https://doi.org/10.3390/ijerph18179391.

Nyrud, A.Q., Bringslimark, T., Bysheim, K., 2014. Benefits from wood interior in a hospital room: a preference study. Architect. Sci. Rev. 57 (2), 125—131. https://doi.org/10.1080/00038628.2013.816933.

Park, E.L., Choi, B.K., 2014. Transformation of classroom spaces: traditional versus active learning classroom in colleges. High Educ. 68 (5), 749—771. https://doi.org/10.1007/s10734-014-9742-0.

Picucci, L., Caffò, A.O., Bosco, A., 2011. Besides navigation accuracy: gender differences in strategy selection and level of spatial confidence. J. Environ. Psychol. 31 (4), 430—438. https://doi.org/10.1016/j.jenvp.2011.01.005.

Pilorz, V., Helfrich-Forster, C., Oster, H., 2018. The role of the circadian clock system in physiology. Pflügers Archiv 470 (2), 227—239. https://doi.org/10.1007/s00424-017-2103-y.

Ramli, N.H., Ahmad, S., Masri, M.H., 2013. Improving the classroom physical environment: classroom users' perception. Procedia-Social and Behavioral Sciences 101, 221—229. https://doi.org/10.1016/j.sbspro.2013.07.195.

Rea, M., Figueiro, M., Bullough, J., 2002. Circadian photobiology: an emerging framework for lighting practice and research. Light. Res. Technol. 34, 177—190. https://doi.org/10.1191/1365782802lt057oa.

Read, M.A., Sugawara, A.I., Brandt, J.A., 1999. Impact of space and color in the physical environment on preschool children's cooperative behavior. Environ. Behav. 31 (3), 413—428. https://doi.org/10.1177/00139169921972173.

Rigolon, A., Alloway, M., 2011. Children and their development as the starting point: a new way to think about the design of elementary schools. Educ. Child Psychol. 28 (1), 64.

Rizzo, A.A., Bowerly, T., Buckwalter, J.G., Klimchuk, D., Mitura, R., Parsons, T.D., 2009. A virtual reality scenario for all seasons: the virtual classroom. CNS Spectr. 11 (1), 35—44. https://doi.org/10.1017/S1092852900024196.

Rodrigues, P.F.S., Pandeirada, J.N.S., 2015. Attention and working memory in elderly: the influence of a distracting environment. Cognit. Process. 16, 97—109. https://doi.org/10.1007/s10339-014-0628-y.

Seidman, L.J., Breiter, H.C., Goodman, J.M., Goldstein, J.M., Woodruff, P.W.R., O'Craven, K., Savoy, R., Tsuang, M.T., Rosen, B.R., 1998. A functional magnetic resonance imaging study of auditory vigilance with low and high information processing demands. Neuropsychology 12 (4), 505—518. https://doi.org/10.1037/0894-4105.12.4.505.

Shamaki, T.A., 2015. Influence of learning environment on students' academic achievement in mathematics: a case study of some selected secondary schools in yobe state-Nigeria. J. Educ. Pract. 6 (34), 40—44.

Shen, J., Zhang, X., Lian, Z., 2020. Impact of wooden versus nonwooden interior designs on office workers' cognitive performance. Percept. Mot. Skills 127 (1), 36—51. https://doi.org/10.1177/0031512519876395.

Slater, M., Usoh, M., Steed, A., 1994. Depth of presence in virtual environments. Presence Teleoperators Virtual Environ. 3, 130—144. https://doi.org/10.1162/pres.1994.3.2.130.

Slater, M., Steed, A., 2000. A virtual presence counter. Presence 9 (5), 413—434. https://doi.org/10.1162/105474600566925.

Sleegers, P.J., Moolenaar, N.M., Galetzka, M., Pruyn, A., Sarroukh, B.E., Van der Zande, B., 2013. Lighting affects students' concentration positively: findings from three Dutch studies. Light. Res. Technol. 45 (2), 159—175. https://doi.org/10.1177/1477153512446099.

Smolders, K.C., De Kort, Y.A., 2014. Bright light and mental fatigue: effects on alertness, vitality, performance and physiological arousal. J. Environ. Psychol. 39, 77—91. https://doi.org/10.1016/j.jenvp.2013.12.010.

Smolders, K.C., De Kort, Y.A., 2017. Investigating daytime effects of correlated colour temperature on experiences, performance, and arousal. J. Environ. Psychol. 50, 80—93. https://doi.org/10.1016/j.jenvp.2017.02.001.

Studer, P., Brucker, J.M., Haag, C., Van Doren, J., Moll, G.H., Heinrich, H., Kratz, O., 2019. Effects of blue-and red-enriched light on attention and sleep in typically developing adolescents. Physiol. Behav. 199, 11—19. https://doi.org/10.1016/j.physbeh.2018.10.015.

Tanner, C.K., 2000. The influence of school architecture on academic achievement. J. Educ. Adm. 38 (4), 309—330. https://doi.org/10.1108/09578230010373598.

Tähkämö, L., Partonen, T., Pesonen, A.K., 2019. Systematic review of light exposure impact on human circadian rhythm. Chronobiol. Int. 36 (2), 151—170. https://doi.org/10.1080/07420528.2018.1527773.

Vandewalle, G., Gais, S., Schabus, M., Balteau, E., Carrier, J., Darsaud, A., Sterpenich, V., Albouy, G., Dijk, J.D., Maquet, P., 2007. Wavelength-dependent modulation of brain responses to a working memory task by daytime light exposure. Cerebr. Cortex 17 (12), 2788—2795. https://doi.org/10.1093/cercor/bhm007.

Viola, A.U., James, L.M., Schlangen, L.J., Dijk, D.J., 2008. Blue-enriched white light in the workplace improves self-reported alertness, performance and sleep quality. Scandinavian Journal of Work 297—306. Environment & Health.

Wannarka, R., Ruhl, K., 2008. Seating arrangements that promote positive academic and behavioural outcomes: a review of empirical research. Support Learn. 23 (2), 89—93. https://doi.org/10.1111/j.1467-9604.2008.00375.x.

Xia, T., Song, L., Wang, T.T., Tan, L., Mo, L., 2016. Exploring the effect of red and blue on cognitive task performances. Front. Psychol. 7, 784. https://doi.org/10.3389/fpsyg.2016.00784.

Xia, G., Henry, P., Queiroz, F., Westland, S., Yu, L., 2022. Colour—cognitive performance interaction in virtual reality (VR): a study of gender differences. Journal of the International Colour Association 28, 1—6.