THE EFFECTS OF ILLUMINANCE ON STUDENTS' MEMORY. A NEUROARCHITECTURE STUDY

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Abstract

Classroom lighting conditions affect students' academic performance due to the influence of light on learning. Illuminance is a lighting parameter recognised as an important factor in interior lighting. The objective of this study is to analyse the effect that a classroom's illuminance exerts on university students' memories; memory is one of the fundamental cognitive processes in learning. Forty subjects performed a psychological memory task in three immersive virtual environments (IVEs) with different illuminance levels, 100 lx, 300 lx and 500 lx. Their neurophysiological responses were monitored during the tasks through electroencephalogram, heart rate variability and electrodermal activity analysis. The results showed that classroom illuminance influences students' memories at psychological and neurophysiological levels. As illuminance increased, their performance in the memory tests deteriorated, and neurophysiological activation diminished; the best results were obtained with an illuminance level of 100 lx. These results may have important consequences for the energy efficiency of educational centres and provide information about the cognitive implications of lighting for learning in virtual environments.

Keywords: classroom design; lighting; memory; neurophysiological responses; neuroarchitecture; immersive virtual environment

Highlights

- The effects of illuminance on psychological and neurophysiological responses are analysed.
- Low lighting improves (100lx) memory performance.
- Low lighting (100lx) increases neurophysiological activation.
- The experiments were performed using virtual reality.

1. INTRODUCTION

New technologies and new teaching methods are changing higher education. These changes have been accelerated by the worldwide public health emergency caused by COVID-19. This has led to the educational spaces becoming more interactive and collaborative. Learning, like all other facets of society, combines physical and virtual reality. It is therefore expected that more and more activities based on virtual reality (VR) will be developed [1]. The educational community has become increasingly interested in adapting learning spaces to address these changes [2]. Nonetheless, the question of how best to adapt the environment of classrooms remains unanswered.

There is a belief that we cannot improve learning without examining, first, how the physical spaces used to deliver instruction are designed and, second, their impact on learning [3]. However, this is a very complicated task because it involves many factors [4][5], such us space, temperature, acoustics, air quality, furniture and light. Light, indeed, has been shown to have an impact on the fundamentals of human life, among them vision, mood, circadian rhythms, daily behaviours, health, wealth and safety [6][7]. The impact of light on vision is the most recognised and obvious [8]. It should be noted, nevertheless, that exposure to light has important effects on human physiology unrelated to visual perception [9]; indeed, the photo-biological effects of light on human beings are less well understood. They were identified due to the discovery in the retina of melanopsin-containing intrinsically photoreceptive retinal ganglion cells (ipRGC) [10][11]. These ganglion cells are thought to play a crucial role in many of the non-visual biological effects of light on humans [12]. These non-image-forming (NIF) effects of light exposure have been shown to have physiological and cognitive impacts on humans [13][14]. They have direct and indirect connections to brain areas implicated in the regulation of arousal [15][16], alertness [17] and emotional responses [18]. IpRGCs have also been found to be related to mood regulation and learning [19]. It is known that light plays a fundamental role in learning environments [20][21][22], and it has been found that lighting conditions affect students' performance [23] and academic achievements [24][25].

However, this new knowledge about the physiological effects of light on humans raises a fundamental question for higher education, that is, which lighting is most suitable for the new technologies and new teaching methods? The answer, of course, is a light that considers not only the effects of light on students' vision, but also its physiological effects. The problem is that nowadays, people in modern society spend most of their time exposed to artificial lights.

Simultaneously, the energy crisis and the carbon impact of buildings have led to increasingly urgent demands to reduce building energy drastically. In the building sector lighting accounts for 19% of global electricity consumption in the building sector [26]. However, in the case of university educational buildings, this percentage rises to 42% of the electricity consumed only for lighting [27]. In this sense, numerous studies can be found regarding lighting analysis, as they require high levels of comfort and energy consumption [28]. Therefore, understanding the complexities of how artificial lighting should be adapted to enhance student cognitive processes and educational changes and, at the same time, linked to the sustainability of the building becomes a significant challenge for researchers.

Among all the parameters of electric lighting (uniformity, colour rendering index, colour temperature, etc.), illuminance is the variable of artificial lighting that has the most significant influence on the energy efficiency of educational centres because a change in the level of illumination can have a great effect on their energy consumption. In fact, illuminance is recognised as a fundamental parameter in indoor lighting [29]. Moreover, illuminance has been revealed to considerably impact subjects' feelings of alertness and task performance [30][31]. Some previous research has shown that low illuminance is associated with decreased cognitive and academic performance [32][33][34]. However, most previous research into the influence of lighting levels on cognitive performance has returned conflicting and inconclusive results. While many studies have shown that illuminance has a positive influence in sustaining attention [35], others have found that differing illumination conditions have no significant effect on task performance [36]. Moreover, other studies have even suggested that participants perform worse in higher illuminance environments [37]. This is due, in part, to the difficulty of comparing results of studies which examine varied intensity (illuminance levels), light wavelengths, timing/duration of exposure and task type and difficulty [12][36][37][38]. Thus, it has been shown that different cognitive tasks seem to need different illumination levels.

If one looks at the type of cognitive tasks that students perform when they are learning, one of the most important is memory. Memory is not only essential for learning, but it is also of great interest in our current society due to its relation to dementia. As with other cognitive processes, the neurophysiological correlates of different illumination conditions and their effects on memory remain unclear. Ru et al. [14], in a laboratory study, found that different levels of illuminance had different effects on working memory in a visual task. Kretschmer et al. [39] found that bright light had positive effects on working memory and arithmetic abilities. Nevertheless, other authors, such as Jung et al. [40], studied the effect of illuminance (400 lx, 700 lx and 1000 lx) on long term memory and suggested that the lower illuminance is the more effective. Others have found no significant differences [36]. In this regard, it should be noted that it seems that task difficulty plays a relevant role in the results. If task difficulty is taken into account, Huiberts et al. [37] found evidence that bright light had more beneficial effects on working memory in the performance of easier tasks than in the performance of difficult tasks; but, for other working memory tasks, this hypothesis was not proven. Smolders et al. [41] showed that bright light, although beneficial for performing vigilance tasks, proved to be detrimental for more complex tasks measuring inhibitory capacity and working memory abilities. Hence, more systematic and recurrent confirmation of the relationship between illuminance and memory is required.

Thus, it is difficult to assess the influence that illumination levels have on working memory; the complexity of the relevant relationships is joined by the challenges of establishing an adequate analysis context and developing methodologies that can collect subjects' responses.

As to the context, most studies have been carried out in laboratories [12][13][29] and, thus, extrapolating their results to real classrooms is difficult. In fact, studies into the effects of lighting in real-life settings face two great difficulties: the high cost of modifying certain lighting variables, and the difficulty of controlling the study conditions to ensure they remain unchanged during the process. Thus, experimentation using physical classrooms has significant methodological limitations. Immersive virtual environments (IVEs) can overcome these two methodological limitations as they influence affective responses and perceptions [42] In fact, virtual reality (VR) technologies have been attracting significant interest in various research fields, including building science and occupant comfort research [43] In any case, using IVEs reduces the time and costs incurred in using real classrooms and laboratories.

Evidence has been found that IVEs can stimulate human responses to light [44]. Indeed, VR has been used to analyse the influence of light on human beings in various study areas and to compare results obtained in studies examining illuminance conditions in VR and real environments. When carefully calibrated, IVEs provide simulations that can be modified dynamically, and which are compatible with the monitoring of behaviours and the measurement of cognitive performance [45][46]. VR can be an effective tool through which to study users' behaviours as it provides a satisfactory representation of the real physical environment [47]. Moreover, VR can simulate environments that, in general, evoke psychological and neurophysiological responses similar to those evoked in real environments [48]. In this context, the validation of the VR used in experiments is the most important step in this type of research as, to analyse their influence on users, it is very important that IVEs faithfully reproduce real environments. Heydarian et al. [47] showed that users' performances in dark and bright conditions were similar to their performances in IVEs and physical environments. Their results showed that participants experienced a strong sense of presence in VR, and that they behaved similarly in virtual settings as they did in real environments. Consequently, they suggested that IVEs are useful tools for acquiring information about users' preferences, behaviours and performance. Chokwitthaya et al. [49] showed that experimental subjects experienced variations in perceived brightness and task performance in VR comparable to those they experienced in physical environments, based on illuminance levels of 200 to 1500 lx. Chen et al. [50] compared reproduction technologies (photographs, video, IVEs) to evaluate illuminance parameters. They analysed participants' perceptions of lighting in VR and real-world scenes and found that VR evoked feelings very similar to those evoked in the real-world scenes. Jin et al. [51] compared the results of a visual acuity task, based on perceived brightness, glare and spaciousness, performed in both a real-world space and a VR environment. They found no significant difference between the rendered-VR simulation and the real-world space in terms of brightness.

VR has also been used to analyse lighting design and users' behaviours due to its ability to allow rapid comparisons to be made between different design options [52]. In this sense, Wong et al. [53] combined building information modelling (BIM) and virtual reality (VR) technologies to evaluate lighting design alternatives and to improve the efficiency of real-time interactive lighting design. Mahmoudzadeh et al. [54] analysed the impact of having personal control over lighting systems on occupants' lighting choices, satisfaction with lighting and task performance in a virtual office setting. Heydarian et al. [55] used IVEs to examine the influence of participants' preferences and personalities on their lighting-related behaviours. Their results showed that participants significantly preferred simulated daylight as a lighting setting and performed better in this condition.

Similarly, VR has been used to evaluate users' perceptions of both natural and artificial illumination. Taking natural illumination, using VR, Moscoso et al. [56] analysed regional differences in perceptions of daylit scenes across Europe by applying variable window sizes and sky type. Regional differences were shown to exist, particularly in how pleasant and calm the participants perceived the environments. Using IVEs, Hegazy et al. [57] used experimental participants' subjective responses to evaluate their perceptions of the brightness of daylight in buildings. Their results showed a statistically significant positive correlation between mean illuminance and participants' perceptions of brightness. Taking artificial illumination, Chokwitthaya et al. [49], in an IVE-based study, showed that users' visual perceptions of brightness increased in proportion to illuminance, and observed significant differences in working performance based on illuminance levels. Using VR, Ma et al. [58] studied the effects of illuminance (200, 500 and 750 lx) and colour temperature (2000, 4000 and 6500 K) on experimental participants. They found that, although statistically significant differences were not observed at 4000 K or 6500 K, at all CCT levels task performance improved in proportion to increases in illuminance. Despite these promising results, as a new field of research, further work is needed to explore the potential of VR in the lighting field.

In the higher education field, the changes brought about by new teaching methods have accelerated due to the worldwide public health emergency caused by COVID-19. In consequence, it is expected that more and more VR-based activities will be undertaken. In fact, VR has already been used to evaluate cognitive processes, such as attention [59] and memory [60], and it has been validated for the assessment of task performance in university classrooms [61] It has also been used to study learning and memory in other contexts, such as offices [62] and apartments [63] It has been suggested that VR is a more efficient and cost-effective tool for quantifying cognitive processes than are physical environments [64].

Psychological tests have traditionally been used to collect subjects' responses. However, these tests are not sufficiently comprehensive to quantify cognitive-emotional states, which are characterised by both psychological and physiological responses [65] One solution to this deficiency is to use, also, neurophysiological measures, which are compatible with VR systems [66]. Neurophysiological metrics record the involuntary component of users' cognitive-emotional responses [67] in a real-time, non-invasive way. Neurophysiological signals are collected while subjects execute psychological tasks and/or complete questionnaires. Among the most recognised measurement tools are: the electroencephalogram (EEG), which measures variations in electrical activity on the surface of the scalp [68]; heart rate variability (HRV), which measures variations in the intervals between heartbeats [69]; and electrodermal activity (EDA; also known as galvanic skin response, GSR), which measures electrical activity through sweat glands in the skin [70]. Some studies examining performance in teaching spaces have found relationships between neurophysiological metrics and cognitive processes related to learning, such as attention and memory [71].

EEG, with the advancement of neurophysiology, has been utilised extensively as an objective indicator to complement traditional subjective and task assessment methods [72][73][74]. EEG EEG is useful for evaluating attention [75][76]. EEGs have been applied to measure electrical activity in the brain and investigate the effect of light conditions on cognitive performance. Park et al. [77] found evidence that illumination conditions modulated brain activity and used EEG to study the effect of illuminance on working memory. Specifically, brighter illumination conditions were associated with significantly lower frontal EEG theta activity during experimental participants' retention periods. Lu et al. [78] utilised EEG to analyse the effect of different combinations of illumination on subjective evaluation and task evaluation. The physiological evaluation showed that the response speed of the visual centre is related to illumination.

HRV, as a physiological response, has also been often employed to analyse the effect of light conditions on cognition [41] and as an index of the autonomic nervous system in illuminated environments [79]. Chamilothori et al. [80] examined how façade geometry, and its interaction with sunlight patterns in VR settings, influenced occupants' subjective and physiological responses (HRV and skin conductance). Their results revealed that façade and sunlight pattern geometry significantly influenced participants' subjective and HRV responses. In addition, it has been shown that attention can be analysed based on HRV [81]. Shah et al. [82] obtained correlations between HRV metrics and learning. Hansen et al. [83] also found correlations between HRV and memory.

EDA is a psychophysiological indicator of emotional arousal [84]. EDA measures changes in the skin's electrical conductance and comprises phasic changes that have been referred to as galvanic skin responses (GSR) that result from sympathetic neuronal activity [85]. EDA measurement has been frequently in studies of consumer emotions [86]. Chinazzo et al. [87] used EDA, with the rest of the physiological variables, to analyse the temperature-colour interaction effects on subjective perception and physiological responses. They employed a hybrid experimental method combining thermal and visual stimuli from real and VR. Thus, it has been shown that neurophysiological recording tools (EEG, HRV and EDA) can be useful, in a complementary way, for quantifying cognitive-emotional processes.

In sum, the objective of this work is to analyse the impact of the illuminance of artificial lighting on the memory of university students (Figure 1). This relationship is comprehensively analysed using students' psychological (a memory task) and neurophysiological responses (EEG, HRV and EDA). The different light stimuli were presented using classroom-based IVEs.

2. MATERIAL AND METHODS

The experiment was conducted in a laboratory setting. A sample of participants was exposed to IVEs of university classrooms with different levels of illuminance. Their psychological and neurophysiological responses were recorded. As to the psychological measures, the IVEs were validated by quantifying the level of presence perceived by the participants (analysed in Phase 1), and memory performance was quantified by means of a set task (analysed in Phase 2a). As to the neurophysiological measures, neurophysiological activation was quantified through EEG, HRV and EDA (analysed in Phase 2b). The experiment was conducted following the Declaration of Helsinki and was approved by the Review Board (Project P1_25_07_18) of the University of which the authors share the affiliation. Figure 1 depicts the overall sequence.

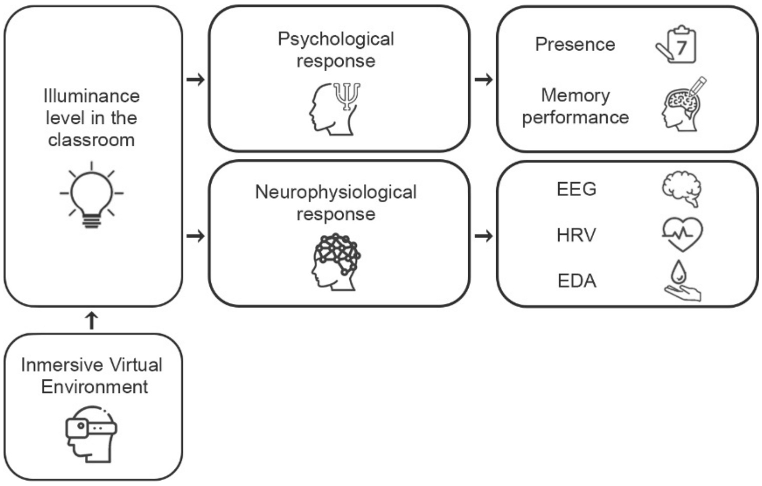

Figure 1. General outline of the methodology.

2.1. Participants

Some 142 participants took part in the study (58 % male, 42 % female; average age 23.17 years, σ = 4.04). There were four inclusion criteria: (1) to be between 18 and 23 years (most common age range of university students in Spain); (2) to be a Spanish university student (to avoid possible cultural effects); (3) to have normal vision, or corrected-to-normal vision with contact lenses, and no colour deficiencies; and (4) to have not consumed performance-altering substances (such as caffeine) in the previous 24 hours.

2.2. IVE

To avoid participants being influenced by daylight during the experiments, the study was conducted in a windowless classroom, and the IVE was also a windowless virtual classroom. A representative example of this type of space in Spain was designed. It measured 16.50 x 8.50 metres and had a nominal capacity of 88 students. The lighting was prepared to simulate tubular lamps with a diameter of 1.62 cm (5/8 inch) and a length of 53 cm) fitted into 56 cm x 56 cm luminaires with a capacity of 4 lamps. The classroom had a total of 45 of these lamps. Figure 2 shows the design, indicating the position of the luminaries.

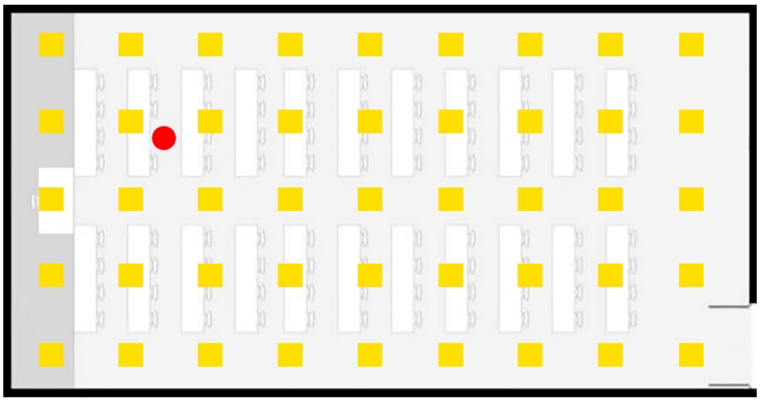

Figure 2. Architectural plan of the IVE (the lights are represented by the shaded boxes, the position of the participant by the circle).

A modelling and rendering process was followed. The modelling was carried out using Rhinoceros (v.5.0), and the rendering by a Vray Renderer (v.3.3), with Autodesk 3ds Max (v.2014). Global illumination was calculated using "irradiance map" (primary) and "light cache" (secondary) calculation engines; these create efficient, physically based lighting simulation. The renders were configured as 360º panoramas, and were saved in a JPG resolution format of 8000 x 4000 pixels. The point of view of the renderings remained constant, that of a "student" sitting in the centre of the second row of tables.

Thereafter, the renders, using Unity3D (v5.6) software, were displayed through the HTC Vive head-mounted device (HMD). This HMD has a total resolution of 2160x1200, a field of view of 110º and a refresh rate of 90Hz. The device was calibrated to ensure the consistency of the colours reproduced, through a process of visual comparison with a calibrated screen. Prior to the start of the experimentation, a pre-test was carried out with 5 participants (who were familiar with the physical classrooms on which the IVE was based) to receive feedback on the experience and its realism. Minor changes in the textures of the materials were adjusted accordingly. The HMD was connected to a high-performance computer (CPU, i9-10900K, RAM 64 GB, GPU RTX3080), allowing a smooth IVEs experience. However, since virtual experiences can lead to motion sickness [88] (by its nature, not by its contents), all participants were informed that they could leave the test in case of any discomfort caused by the experimentation. None of the 142 participants withdraw from the experimental session. Figure 3 shows a participant taking part in the experiment.

Figure 3. Participant taking part in the experiment.

2.3. Illuminance configurations

In the experiment three different illuminance levels were presented: 100 lx, 300 lx and 500 lx. To ensure that these levels were correct in the virtual environment "VRayLightMeter" was used. This tool (native in the rendering software) works in a similar way to a real-life light meter but with the particularity of covering the desired surface area. Hence, VRayLightMeter was placed at the level of the working plane (that is, the participant's virtual table) taking a dimension of 3.50 x 3.50 meters (1.50 meters on each side of the participant's virtual position in the classroom). Subsequently an iterative rendering process was carried out, modifying the illumination power (identically for all lamps) until an average level equal to the chosen one was reached in this area. This was replicated for each of the three illuminance levels. In line with recent research [89], considering the physically realistic capability of the rendering software and the performance of the HMD the correspondence of the IVEs to physical (real) environments was considered as achieved. Figure 4 shows the tool in use, taking the example of the 300 lx IVE.

IVEs were generated with the three illuminance levels (Figure 5). The three levels were viewed by all participants, following a complete counterbalanced order (to avoid biases caused by repeated exposure to the IVEs). A break of 60 seconds was inserted between the IVE viewings, during which the participants listened to a relaxing audio track featuring sounds of nature.

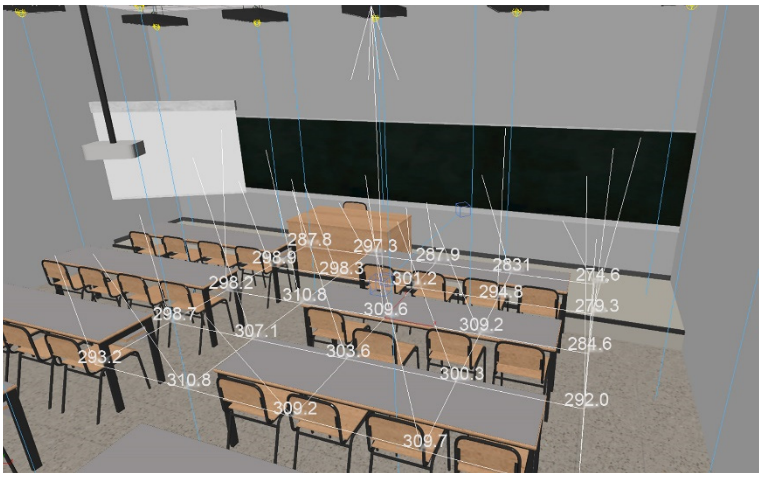

Figure 4. Configuration of the lighting for the rendering of the IVEs.

Figure 5. IVE simulations.

2.4. Psychological measures

The psychological measures quantified sense of presence in the IVEs and memory performance.

2.4.1. Sense of presence

Sense of presence was measured to assess the validity of the IVEs. Sense of presence is the illusion of "being there" [90] in an environmental simulation. Following their exposures to the IVEs, the participants completed the SUS questionnaire [91], which consists of six items measured on a Likert-type scale, from 1 to 7.

2.4.2. Memory performance

A psychological task was set to assess the memory performance of the participants in each IVE scenario. The participants undertook the task after 60 seconds of silently viewing the IVEs. The task was similar to the Deese-Roediger-McDermott (DRM) paradigm experiments, a cognitive psychology technique used to study false memory in humans [92], which involve memorising lists of 15 words associated with a concept not explicitly revealed. To avoid the possible effects that might be caused by the intensity of the ambient light on visual capability and comfort (which could have an impact on task performance), the words were presented orally, not visually. The participants listened to recordings of the lists produced through Loquendo TTS (v.7) and had to repeat them in a maximum time of 30 seconds. This was repeated three times for each IVE, so nine lists (3 lists x 3 IVE) of words were chosen, all presented counterbalanced. Following the procedures, the interviewer recorded the number of hits on each list and adjusted the number of words remembered based on the recall rate proposed by Alonso et al. (specifically, word lists of "cinema", "smoke", "injury", "moon", "shoe", "guitar", "place", "butterfly", and "song") [93]. This produces a psychological metric "memory-correct answers", with higher values indicating better performance.

2.5. Neurophysiological measures

Neurophysiological activation was measured through EEG, HRV and EDA. Recordings were taken at two points: (1) prior to the IVE viewings (to establish a baseline state for each participant, which was used to normalise the data); and (2) during the 60 seconds of silent viewing of each IVE.

2.5.1. EEG

EEG was measured using the b-Alert x10 device. This recording system has nine passive electrodes (located in the frontal -Fz, F3, F4-, central -Cz, C3, C4-, and parietal -POz, P3, P4- regions based on the international 10–20 electrode placement; reference electrodes on the masteoids) which cover a unit area of 1.77 cm2 and are connected to the scalp by a gel-infused foam. The raw signal, sampled at 256 Hz, was pre-processed and analysed using EEGLAB [94] with Matlab (v.2016a) conducting a power spectral analysis. This analysis, often used to analyse EEG, makes it possible to quantify the amount of activity in certain frequency bands of the signal (based on the idea that different networks operate in the brain, each at its own frequency [95]. The highbeta band (21-30 Hz) of the Fz electrode signal was calculated. This choice was made because this frequency band is associated with alertness [96], and the frontal lobe (where the electrode is located, in a central position) is associated with processes such as working memory [97]. The values were expressed in relative power [98] This produced the neurophysiological metric EEG-FzHighbeta.

2.5.2. HRV

Again, the b-Alert x10 device was used. For this purpose, two electrodes are placed on parts of the participant with little potential movement (specifically, on the last floating rib on the left side and the right clavicle). The raw signal, sampled at 256 Hz, was pre-processed and analysed using HRVAS (v.2014-03-21) with Matlab (v.2012a) conducting a frequency analysis, with proven clinical and cognitive-emotional significance [99]. The low frequency band of the signal (0.05-0.15 Hz) was calculated. This choice was made because this frequency band is associated with sympathetic system activity [100]; higher values being associated with increased arousal. It was expressed in normalised units [101]. This produced the neurophysiological metric HRV-nLF.

2.5.3. EDA

The Shimmer 3GSR+ device measured the EDA. Two electrodes were placed on two fingers (specifically, on the middle phalanx of the index and middle fingers) of the participant's non-dominant hand (to avoid the noise generated by movement during the execution of the psychological tasks). The raw signal, sampled at 128 Hz, was pre-processed and analysed using Ledalab (v.3.4.8) with Matlab (v.2016a) conducting a Continuous Decomposition Analysis [99] to the cleaned signal to extract the phasic component. The phasic component of the signal was calculated. The choice was made because this component is associated with sympathetic system activity [102][84]. To reduce data variability between the subjects the values were normalised following Venables and Christie [103]. This produced the neurophysiological metric EDA-Phasic.

2.6. Data Analysis

The data analysis was carried out in 2 phases (Table 2). IBM SPSS software was used (v.17.0, IBM, Armonk, NY, USA). In the first phase, the level of presence produced by the different VR simulations was calculated, by summing the averages of the six items of the SUS questionnaire [91]. In the second phase, the effects of the different illuminance conditions on the students' memory were calculated, using statistical comparison techniques. Thus, we analysed the effects of the different illuminance levels (100lx-300lx-500lx) on the students' memories and on their neurophysiological activity (HRV, EEG and EDA). Since the variables were pre-standardised, analyses of variance (ANOVA) were applied. A Bonferroni post-hoc analysis was then applied to identify any differences between them.

Phase	Analysis and Data Used	Statistical Treatment	Expected Result
Phase 1 Validation of the IVEs.	Analysis of level of sense of presence. SUS-Total	Descriptive analysis of means.	Sufficient level of sense of presence.

Phase 2 Analysis of psychological and neurophysiological responses	Phase 2a. Analysis of psychological response: Memory-correct answers Phase 2b. Analysis of psychological response: EEG-FzHighbeta HRV-nLF EDA-Phasic	ANOVA and Bonferroni's post hoc analysis, as a function of illuminance (100lx-300lx-500lx).	Significant differences in memory performance and neurophysiological metrics based on classroom illuminance. Identification of the illuminances which gave the best and worst memory performances and highest and lowest neuropsychological activity.

Table 2. Statistical treatments.

3. RESULTS

The following section discusses the results of the two stages, validation of the IVEs and the analysis of the psychological and neurophysiological responses.

3.1. Phase 1: Validation of the IVEs

The SUS questionnaire [91] was used to obtain the presence levels of each illuminance configuration. This tool consists of six items that measure three aspects of the sensation of presence: being inside the simulation, regarding the simulation as real and remembering the simulation as a place. The items should be rated on a 7-point Likert scale. Table 3 shows the results obtained for each item. The mean of the set of items is 5.1 out of 7. The sum of the six items provides the SUS-Total metric which exceeded the 29 points. Based on the evidence provided by previous studies into presence [104] it can be concluded that the simulations were satisfactory.

Item	**Illuminance**		
	100 lx	**300 lx**	**500 lx**
1. I had a sense of ''being there'' in the classroom space	5.16 *(1.239)*	5.45 *(0.989)*	5.24 *(1.453)*
2. There were times during the experience when the classroom space was the reality for me	4.67 *(1.425)*	5.11 *(1.211)*	4.83 *(1.665)*
3. The classroom space seems to me to be like somewhere that I visited before	5.08 *(1.581)*	5.66 *(1.330)*	5.22 *(1.686)*
4. During the experience you felt you were in the classroom space	4.90 *(1.348)*	5.34 *(1.194)*	4.93 *(1.314)*
5. I think of the classroom space as a place similar to other places that I've been today	4.86 *(1.880)*	4.66 *(1.796)*	4.89 *(1.729)*
6. During the experience I often thought that I was really in the classroom space	4.94 *(1.928)*	5.02 *(1.688)*	5.46 *(1.445)*
SUS-Total	**29.61**	**31.23**	**30.57**

Table 3. Level of sense of presence for each item of the SUS questionnaire (mean and standard deviation).

Following validation of the VR environment, the students' psychological and neurophysiological responses were analysed. The differences in user response for each illuminance level (100 lx-300 lx - 500 lx) were analysed using statistical comparison techniques. Given the normality of the variables, ANOVA tests were applied.

3.2. Phase 2a: Analysis of the psychological responses (memory performance)

The average levels of memory-correct answers in each situation were obtained. Figure 6 shows a progressive reduction in memory performance as illuminance increased. The best performance was achieved with low lighting (100 lx). The ANOVA test showed significant differences in memory performance as a function of illuminance (*p=0.003*). The Bonferroni post hoc analysis showed a significant reduction of memory test performance as illuminance increased from 100 lx to 300 lx (p=0.037), and from 100 lx to 500 lx (p=0.003). However, no significant difference was observed between the 300 lx and 500 lx (p>0.05) levels.

3.3. Phase 2b: Analysis of the neuropsychological responses (EEG, HRV and EDA)

The average levels of EEG-FzHighbeta, HRV-nLF and EDA-Phasic were obtained for each scenario.

3.3.1. EEG Fz-HighBeta

The results showed that higher illuminance was associated with lower EEG-FZ Highbeta values (Figure 6). The ANOVA showed significant differences (p=0.002) in this metric as a function of illuminance. The Bonferroni post hoc analysis showed this difference arose between the 100 lx and the 300 lx (*p=0.05*) conditions, and between the 100 lx and 500 lx (p=0.002) conditions.

3.3.2. HRV-nLF

The results showed that, as illuminance increased, the average levels of heart activation decreased (Figure 6). The 100 lx illuminance level was associated with the highest sympathetic system activation. The ANOVA showed significant differences in the HRV-nLF metric based on classroom illuminance *(p=0.015).* The Bonferroni post hoc analysis showed that this difference arose between the 100 lx and the 500 lx lighting (*p=0.016*) conditions.

3.3.3. EDA-Phasic

The results showed that higher illuminance was associated with lower EDA-Phasic values (Figure 6). The ANOVA showed significant differences in this metric as a function of illuminance (p=0.002). The Bonferroni post hoc analysis showed that these differences arose between the 100 lx and the 300 lx *(p=0.004)* conditions*,* and between the 100 lx and 500 lx *(p=0.014)* conditions.

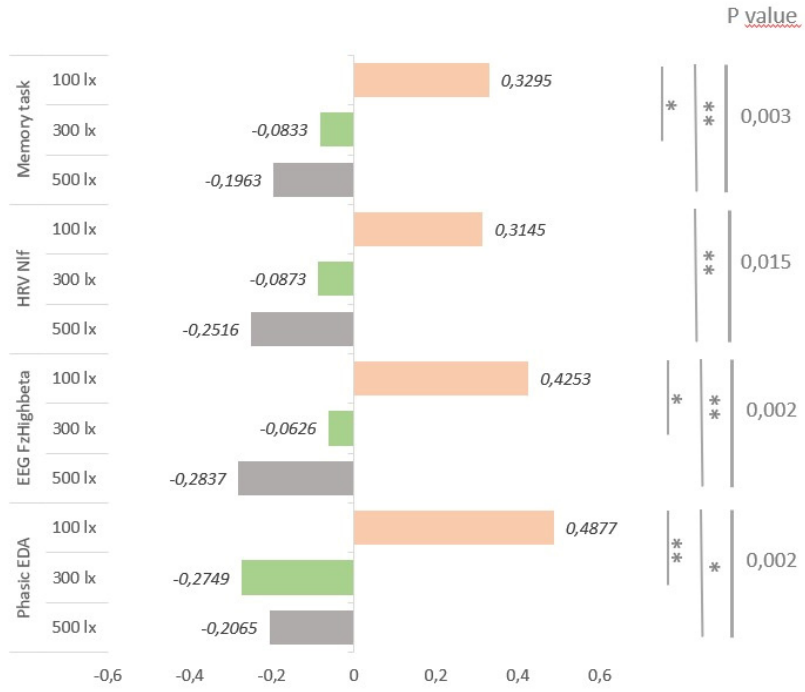

Figure 6. Averages of the psychological and neurophysiological metrics. Asterisks indicate the significance level (*p < 0.05, **p < 0.01).

4. DISCUSSION

The present study analyses the impact of the illuminance of university classrooms on the memories of university students. It investigates responses related to cognitive functions at psychological (memory task) and neurophysiological levels (HRV-nLF, EEG Fz-HighBeta and EDA-Phasic metrics).

The contributions of the present study are to two areas, methodology and results.

At the methodological level, two aspects should be highlighted: (1) task performance can be assessed in a VR-based, simulated lighting environment; and (2) the compatibility of VR systems with neurophysiological metrics.

As to the first point, the present study showed that VR can be used to simulate lighting environments and can be incorporated into the analysis of task performance to assess experimental participants' cognitive performance. IVEs can make significant contributions to the lighting/ architectural field as they generate user responses similar to those produced in real environments [48]. The present work, as have others, emphasises the utility of VR for studying the effects of lighting on humans. VR allows researchers to easily modify and isolate some variables while controlling others, which helps reduce costs. For example, if researchers wanted to change the luminaires, lower the ceiling height, or modify some of the classroom space or lighting, leaving the rest unchanged, it would be very complicated and costly to do so in physical space. However, VR allows these changes to be made quickly and cost-effectively. Moreover, VR not only helps researchers control environmental variables, but it is also compatible with psychological and neurophysiological measures [105]. In other words, the subjects can be in the virtual environment and, at the same time, they can be asked directly and, therefore, their psychological responses can be collected, but it is also possible to collect all their physiological signals, since all the physiological measurement devices can be attached or adapted to them. Therefore, this allows to collect the complete response of the subjects in this virtual environment. In this sense, although VR has been used, and validated, to measure memory [106] and student performance [107], very few studies have identified VR-based lighting design guidelines that can improve students' cognitive performance. However, this study establishes that VR can be used to analyse subjects' cognitive performance in a memory task using different lighting scenarios.

The use of VR to analyse cognitive response is particularly relevant in Higher Education due to the continuous introduction of new technologies and teaching methods. The recent global health emergency has accelerated these changes. Consequently, more and more VR-based activities are expected to be implemented [108]. In this respect, research such as the present study can be fundamental in helping to improve the lighting designs of these new learning environments. Analyses of this kind could help to establish the best lighting environment for learners to perform a given task and, in this manner, help them to improve their learning.

Second, the compatibility of VR and neurophysiological measurement systems represents a meaningful methodological cooperation [66][60]. Analysing both the neurophysiological and psychological responses of experimental subjects in virtual lighting environments, that can be modified and controlled, can provide new insights in the lighting and educational fields. Indeed, several authors have employed VR to measure neurophysiological responses to lighting [80], and others have used virtual classrooms to measure students' cognitive performance [60][109]. However, to the best of the authors' knowledge, no previous studies have used a combination of both measurement systems to examine the cognitive effects of lighting variables in virtual educational environments.

At the results level, two important aspects should be highlighted, that is: (1) the psychological effects; and (2) the neurophysiological effects of illuminance on students' memories. Using combinations of these results researchers can identify the levels of lighting that enhance memory in the context of university classrooms.

First, as to the psychological effects, the results showed significant differences in memory task performance as a function of illuminance level. The best results in the memory task (memory-correct answers) were obtained in the low illuminance (100 lx) scenario. These results agree with those obtained by Jung et al. [40], who suggested that the lowest illuminance was the most effective for memory. Their study analysed the influence of illuminance (400 lx, 700 lx and 1000 lx) in memory. Their experiment indicated that the condition of 400 lx was the more effective. In the same vein, C. W. Lee et al. [110] compared the influence of illuminance (300 vs. 1000 lx) on a memory task. Their results showed statistically significant differences in memory in the dim light condition. Smolders et al. [111] also examined the effects of illuminance (200 vs. 1000 lx) on working memory. Their results showed a significant effect on the percentage of correct responses at the lower illumination level. In our case, for 4000 K, the best results are also obtained for a lower illumination level. In this sense, it is worth remembering that the task's difficulty seems to play a relevant role in the results obtained. Huiberts et al. [37] observe that the effect of task difficulty may play a role in the effect of illuminance level on memory. They investigated the effect of illumination level (200 vs. 1000 lx) on task performance as a function of task difficulty. They found better performance on the most difficult auditory working memory task (similar to the one used in our study) when participants were subjected to the lowest illumination level. Hence, in general, experimental results have suggested that increased illuminance reduces performance in a difficult memory task.

These results have fundamental importance for the energy efficiency of educational centres. In line with other research [112], they suggest that it should be possible to redesign the luminous environment with less energy consumption required and, in addition, to create a lighting environment much more adapted to the tasks carried out in the classroom. Thus, it could be realisable to improve the energy consumption of educational centres and their students' learning.

Second, as to the neurophysiological effects, significant differences were identified in the neurophysiological metrics (EEG Fz-HighBeta, HRV-nLF, and EDA-Phasic metrics) as a function of illumination level. Regarding the EEG, the highest activation level was in the lowest illuminance scenario. This result is in line with that obtained by Park et al. [77] who, using EEG, in a laboratory study, investigated the effects of illumination conditions on mental working efficacy. These authors provided objective evidence that illumination conditions modulate brain activity. In their case, brighter illumination conditions were associated with significantly lower frontal EEG theta activity. Regarding the HRV metric, it was observed that as illuminance decreased, activation levels increased. These results are consistent with other works that have identified relationships between high HRV activity and enhanced memory task performance [83]. Along the same lines, Seo and Kim [113], in a laboratory study, showed that sympathetic activation (HRV-LF) was significantly influenced by illuminance. They found that HRV-LF values were associated with higher illuminance and concluded that higher illuminance levels are associated with less nervous, less "excited" states. Regarding EDA, the results were similar: increased illuminance was associated with reduced levels of phasic EDA. EDA is a psychophysiological indicator of emotional arousal [86]. However, in previous works the results of the effects of this parameter in relation to illumination levels were inconclusive. While some studies have indicated that skin conductance is the psychophysiological measure most sensitive to changes in activity and lighting [114], others did not identify significant differences [80]. For example, Huiberts et al. [115] in a laboratory study, found no significant differences in skin conductance levels with varied lighting levels when difficult tasks (as is the case with the present study) were being performed.

The results of the present study showed that the 100 lx scenario was associated with the best memory task performance, and the highest activation levels in the HRV, EEG and EDA metrics. An important change occurs between the 100 lx and 300 lx scenarios, and even more so between the 100 lx and 500 lx scenarios, in which the differences in all metrics were significant. However, no significant differences were detected between the 300 lx and 500 lx scenarios. This result is of interest because it suggests that task performance and neurophysiological metrics go in the same direction. This relationship is interesting because neurophysiological measurements allow data to be recorded in real time and precludes any possibility of subjects manipulating the outcomes. From this information it is possible to design or, at least, approximate a neurophysiological index (combining several metrics) that can characterise the cognitive responses of subjects to architectural spaces [67].

The present study has some limitations. First, time of day was not controlled because this would have required a very large sample. As Spanish universities use their classrooms for many hours a day (8:00–21:00), future studies might explore if measures taken at different times yield the same results. Second, all lighting variables were kept constant, apart from lighting level. Although illuminance is an important lighting factor, more diverse lighting variables need to be examined to achieve an exhaustive understanding of human responses to VR-based lighting environments.

It would be interesting to see if the results of the present study remain consistent when other lighting design variables (such as uniformity and/or colour temperature) are modified, and to analyse the joint effect of combinations of these variables. Similarly, given that only one classroom was used in the present study, it would be interesting to assess whether different classroom designs would produce different effects. Third, VR can induce students to focus more on enjoying the experience than on correctly performing the task [116]. It would be interesting to address this issue in future studies to establish protocols that persuade participants to fully and adequately involve themselves in tasks in VR-based lighting environments. Finally, the presence of other students, and using different viewpoint positions within the classroom, may have a considerable influence on task performance. In the present study, these factors were excluded due to parameterisation difficulties. Future research might examine these effects and the behaviour and positions of the students in relation to the tasks they perform in the classroom.

5. CONCLUSIONS

The aim of this research is to analyse the impact of the illuminance of classrooms on university students' memories using psychological and physiological metrics.

The results showed that reducing illuminance significantly improves memory performance and sympathetic system activation (i.e., higher levels of HRV-nLF, EEG Fz-Highbeta and EDA-Phasic metrics). The best results in the memory tasks and the highest neurophysiological activation were obtained in the low lighting level scenario (100 lx).

Although further research is necessary, the methodology used may be of interest to future researchers in this field. Similarly, the results of the study can be used by architects and designers to establish lighting design guidelines capable of improving students' cognitive processes.

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