The influence of classroom width on attention and memory. Virtual-reality-based task performance and neurophysiological effects.

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Abstract

Classroom design influences the cognitive processes that determine learning. However, the effects of classroom geometry have been little studied, in part due to the difficulty of modifying physical spaces for experimental purposes. Today, virtual reality allows researchers to very closely control many environmental conditions while collecting psychological and neurophysiological metrics of the user experience. The objective of the present study is to analyse the influence of classroom width on the attention and memory performance of university students. The performance of 90 subjects in three classroom width settings (8.80m, 8.20m, and 7.60m), implemented in virtual reality, was evaluated through measures of their attention- and memory-related psychological and neurophysiological responses. The results showed that wider classrooms are associated with poorer performance and lower emotional arousal. This demonstrates a link between the geometric variables of classrooms and the cognitive and physiological responses of students. In general, the present study and its methodology can help architects and researchers develop design guidelines that can improve students' cognitive processes.

Keywords: classroom design; attention; memory; neuroarchitecture

Introduction

Many studies have shown that classroom-related physical stimuli influence determinant cognitive learning functions such as memory and attention (Choi et al., 2014). Memory and attention are strongly linked, as the early part of the attentional process is the processing and storing in the memory of the stimuli captured by the senses. Memory is the mental process by which people fix and preserve lived experiences and update them according to the needs of the present (Celada & Cairo, 1990). Memory retains information, and attention is one of the factors associated with proper memory function; this function has been defined as the effort made by individuals in both the information storage, and retrieval, phases (Bernabéu, 2017).

Awareness of the cognitive effects on students of their surroundings has created a growing interest in analysing the relationship between physical environments and learning (Yang et al., 2013). However, the relationship is complex to research; first, because of the diversity of the variables involved (Higgins et al., 2005) and, second, because their cognitive-emotional and neurophysiological effects can be closely intertwined (Evans & Stecker, 2004). Thus, many variables have not, as yet, been fully explored.

Environmental variables (temperature, air quality, acoustics, lighting, colour) have been examined. It has been suggested that temperature and air quality are two of the variables most likely to affect students' behaviours and results (Choi et al., 2014; Schneider, 2002). However, the importance of classroom acoustics and lighting have also been stressed. Several acoustic parameters have been shown to negatively affect the learning process, among them noise, reverberation, and the distance between speaker and listener (Crandell & Smaldino, 2000; Picard & Bradley, 2001). As regard to lighting, it has been shown that large windows are associated with better learning results and, in particular, that natural light positively influences reading and science activities (Heschong et al., 2002; Tanner, 2009). Thus, it has been found that when lighting is insufficient or inappropriate (Cook, 1990; Winterbottom & Wilkins, 2009) students have more difficulty with visual learning tasks (Maiden & Foreman, 1998) such as reading texts, which influences their attitudes towards learning and their performance (Dunn et al., 1985; Tanner, 2000). At the same time, some authors have observed that higher lighting colour temperature generates greater cognitive processing and better concentration (Keis et al., 2014). There is also evidence that the colour of an architectural environment influences students' emotions, physiology, and performance (Gaines & Curry, 2011; Küller et al., 2006, 2009). Furthermore, colour has been shown to reduce visual fatigue, improve orientation, facilitate cooperative behaviour among students (Read et al., 1999), and enhance the performance of cognitive functions (Engelbrecht, 2003). Many studies have shown that environmental variables have a strong influence on student performance.

Spatial variables, for example, size and shape, have been less studied. They often form part of national/regional technical building codes, of recommendatory and compulsory natures. These codes may define the range of values that design variables must comply with, for example, the minimum ceiling height of educational facilities. While, in most cases, building codes are sufficiently flexible and broad to accommodate a variety of final designs, designers, to an extent, face important constraints. Few works have examined the effects of spatial variables on student performance (Roskos & Neuman, 2011; Yang et al., 2013). Some studies, however, have emphasised the significance of these variables. Ceiling height is an important example. It has been found that higher ceilings increase teacher satisfaction by reducing perceptions of overcrowding (Ahrentzen & Evans, 1984), and that lower ceilings increase student cooperation (Read et al., 1999). Thus, there are reasons to consider the analysis of further spatial variables as important. However, no specific studies have been found that analyse the spatial variable width.

Most of these studies were undertaken in physical classrooms. This entailed the researchers either selecting a classroom and modifying the variables under study (Marchand et al., 2014), or selecting a set of classrooms of different designs (Yang et al., 2013) to study the effects of the variables. The physical classroom approach has two methodological difficulties. On the one hand, the high cost of modifying some design variables. On the other, the difficulty of tightly controlling study conditions to allow ceteris paribus logic to be applied. The analysis of the effects of any one design attribute can only be successfully achieved if the other variables present remain stable, otherwise they may operate as uncontrolled confounding factors, and create bias in the results. Thus, physical classroom-based experiments have major limitations. This is the case, above all, when studying variables that affect spatial geometry.

The methodological limitations of physical stimuli can be overcome by virtual reality (VR). VR allows researchers to create interactive computer representations that give the user the feeling of 'being there' (Steuer, 1992) in a space that they do not perceive as synthetic (Smith, 2015). The latest advances in computer-generated images simulate light, texture and atmospheric effects to such a degree of photorealism that it is possible to produce a virtual image that is indistinguishable, to the naked eye, from a photograph of a real-world scene (Morinaga et al., 2018). These representations can be dynamically altered, and allow behaviour to be monitored and cognitive performance to be recorded (Parasuraman & Rizzo, 2006; Rizzo et al., 2002). Moreover, VR allows the time and cost-effective isolation and modification of variables under controlled laboratory conditions (Vince, 2004), unfeasible in real space (Alcañiz et al., 2003). In the specific classroom context, VR has been used to assess attention problems (Díaz-Orueta et al., 2014; Iriarte et al., 2012). It has also been used to study learning and memory in other contexts, such as offices (Matheis et al., 2007) and apartment dwellings (Banville et al., 2010). It has been suggested that VR is a more efficient and profitable tool than physical environments in the quantification of cognitive processes (Rizzo et al., 2004).

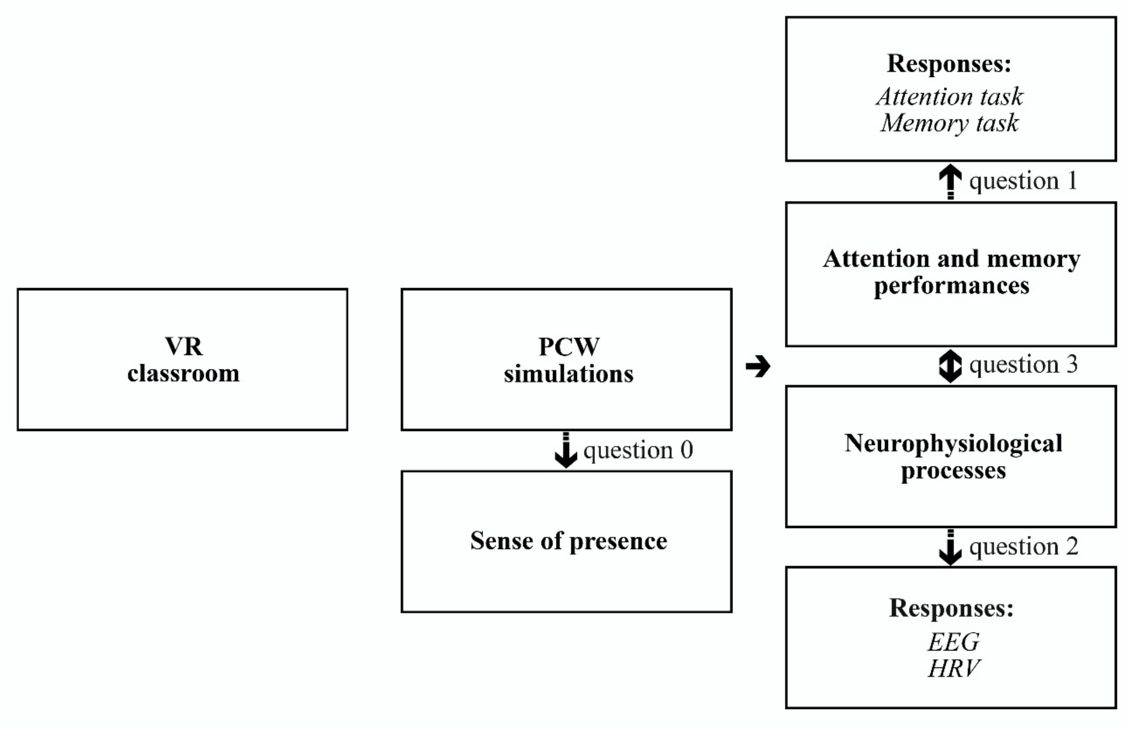
Regardless of the physical or virtual nature of the stimuli, there is a parallel limitation, that is, the system of quantification of cognitive functions. Individual performance has been evaluated through the execution of specific activities, analysing successes / errors / reaction times, for example, in studies based on clerical tasks and proofreading (Cho et al., 2002; Marchand et al., 2014; Rizzo et al., 2004), although it has also been quantified by subjects' self-assessments of their levels of attention and memory (Garnier-Dykstra et al., 2010). It is accepted that both systems are capable of performing cognitive assessments but, nevertheless, psychological tests, which have been traditionally used, cannot fully quantify cognitive-emotional states, which are characterised by both psychological and physiological responses (Izard, 1992). This limitation can be overcome by using neurophysiological measures which, today, are compatible with VR systems (Hemeida & Mostafa, 2017; Higuera-Trujillo et al., 2020).

Neurophysiological measures allow researchers to record the involuntary component of the user's cognitive-emotional responses (Dimoka et al., 2012). This can be done non-invasively in real time while the experimental subject undertakes a psychological task or completes a questionnaire. There are a variety of recordable neurophysiological signals. These include the electroencephalogram (EEG), which measures variations in the electrical activity of the surface of the scalp (Niedermeyer & da Silva, 2005); and heart rate variability (HRV), which measures variations in the intervals between heartbeats (Goldman, 1976). Studies in the literature have found that there are relationships between these metrics and cognitive processes in relation to learning, attention, and memory (Başar et al., 1999). Ko et al. (2017) found a correlation between EEG metrics and attentional performance in the classroom, and Cho et al. (2002) used EEG in a system to improve attentional performance in virtual classrooms. Shah et al. (2011) found a correlation between HRV metrics and learning, and Hansen et al. (2003) between attention and memory. Thus, it has been demonstrated that neurophysiological measures are useful, complementary tools in the quantification of cognitive-emotional processes.

The objective of this paper is to analyse the influence that classroom width has on the attention and memory performance of university students. To overcome the limitations described above, the classrooms were generated in virtual reality and cognitive performance was quantified through the analysis of both psychological and neurophysiological responses. The objective was addressed by posing three questions: (1) Does variation in classroom width significantly influence the psychological performance measures of attention and memory? (2) Do different classroom widths affect some of the neurophysiological processes related to attention and memory? (3) Is there a correlation between the psychological and neurophysiological metrics used?

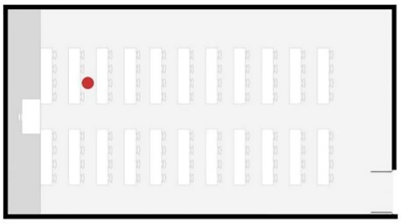
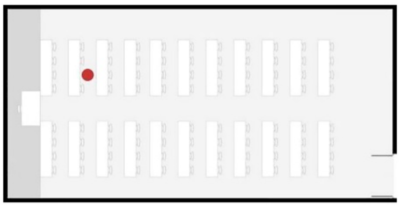
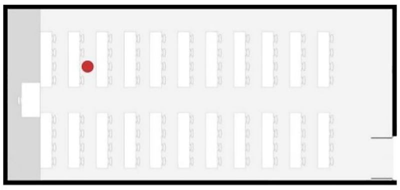
Materials and methods

The experimental methodology was a laboratory study. Comparisons were made of the effect of different parameterisations of classroom width (PCW), displayed through VR, on the subjects' psychological and neurophysiological responses. The analysis methodology consisted of a four-phase field study, with the last three focused on exploring the three questions posed to address the study's objective: (0) validation of the VR environment; (1) an examination of attention and memory performance using psychological metrics; (2) an examination of the underlying cognitive processes using neurophysiological metrics; (3) an examination of the correlation between the psychological and neurophysiological metrics. Figure 1 shows the general methodological outline.



Stimuli

A representative physical university classroom was chosen for the virtualisation. Specifically, a classroom in the Higher Technical School of Building Engineering (ETSIE) at the Polytechnic University of Valencia. The classroom is used for lectures, and the students spend a significant amount of time there. It measures 16.50 by 8.80 meters. Three PCWs of the virtual base classroom were configured: 8.80 m (PCW # A), 8.20 m (width of PCW # A - 0.60 m), and 7.60 m (width of PCW # A - 1.20 m). Thus, the three PCWs were identical, except, obviously, for the widths of the classrooms. The differences are not large, but are visible from the subjects' point of view. The aim was to establish parameterisations that were not so dramatic that they generated side effects in the subjects (e.g. claustrophobia or excitement), and that made sense in building construction terms (0.6 m is one of the standard measurements, for example, for false ceiling and floors). Each subject was shown all three parameterisations. The visualisation order was not the same for all subjects; it followed a complete counterbalancing design to prevent any bias that might be caused by the stimuli presentation sequence. The three stimuli (the three PCWs) provide six different presentation sequencing options (each of which was viewed by 15 subjects: 90 subjects / 6 groups). Figure 2 shows the three PCW simulations (the distortion is due to the display of the 3D environments in 2D; when viewed from the virtual reality device the scene appears natural).

	VIRTUAL CLASSROOM	WIDTH	PLAN OF THE CLASSROOM
PCW#01		8.80 m	
PCW #02		8.20 m	
PCW #03		7.60 m	

Environmental simulation set-ups

The subjects experienced the PCWs through VR simulations in head-mounted displays (HMDs).

The simulations were developed through a process of modelling and rendering. The modelling was carried out using Rhinoceros (v.5.0; www.rhino3d.com), and the rendering through Corona Renderer (v.2.0; https://corona-renderer.com). All the PCW renderings were made from the viewpoint of a student seated in the middle of the second row of desks. The virtual implementation was undertaken using Unity3D (v5.6; www.unity3d.com).

The HMD used was an HTC Vive device (www.vive.com). This has a resolution of 1080 × 1200 pixels per eye (2160 × 1200 in total), with a field of view of 110º and a refresh rate of 90Hz. Figure 3 shows subjects taking part in the experiment.

Subjects

90 subjects participated in the field study. Specifically, the sample consisted of 57% males and 43% females, with average age of 23.56 years (σ = 3,433). Three inclusion criteria were established: (1) being a university student between 18 and 23 years old (the most common age range of students taking university degrees in Spain); (2) being Spanish (to avoid any cultural effects); and (3) having normal or corrected-to-normal vision with contact lenses (to avoid the problems that wearing spectacles can cause with HMDs). The study was undertaken in accordance with the Declaration of Helsinki, and the experimental methodology was approved by the review board of the university with which the authors are affiliated (Project BIA2017-86157-R). Figure 4 shows the general experimental sequence.

	CONCEPT	TIME (MINUTES)	
Preparation	**SUBJECT INITIATION** Reception, basic instructions, signing of consent form, fitting of neurophysiological recording devices.	≈10	↧
	TEST SCENARIO Viewing a test scenario, to adjust the environmental simulation device and acclimatise the subject.	≈2	
Pre-experiment	**BASELINE** Eyes open and eyes closed.	3 (1.5+1.5)	
	GENERAL INSTRUCTIONS *"You will first hear an audio clip. Then you will see yourself in a space. Imagine that it is a university classroom in which you are taking a class. Look at the scenario for 90 seconds. Thereafter, you will complete a series of tasks and questionnaires".*	≈1	
Classroom Experiment	**PREPARATION AUDIO** Relaxing audio to reduce fatigue before repetition of the sequence.	1	**→PCW#A→#2→#3 (Figure 3, counterbalanced)**
	CLASSROOM EXPERIMENT Environmental simulation of the assigned PCW. Metrics: Neurophysiological recordings (HRV-HF; EEG-C3-Beta, EEG-CZ-Highbeta).	1	
	PSYCHOLOGICAL ATTENTION TASK *"You will now hear a series of sounds. You must react as soon as possible to a specific stimulus with a single mouse click, and avoid doing so with others. The stimulus you should react to is this [sound # 1]; and the stimuli that you should ignore are [sound # 2, sound # 3, sound # 4, sound # 5].* Metrics: psychological task (Attention-Time, Attention-Errors).	4	
	PSYCHOLOGICAL MEMORY TASK *"You will hear a series of words. Try to remember them. You will be asked to repeat the words, in any order, within 30 seconds. You should do this 3 times."* Metrics: psychological task (Memory-Correct answers).	4	
	EVALUATION OF THE VIRTUAL CLASSROOM EXPERIMENT Metric: psychological questionnaire (SUS-Total).	≈1	
Post-experiment	**DEMOGRAPHIC QUESTIONNAIRE** Demographic questionnaire.	≈1	⤓
	SUBJECT EXIT PROTOCOL Retrieval of the devices, accompany subject to the exit.	≈5	
	TOTAL:	**55**	

Data analysis

Psychological and neurophysiological data were recorded for all subjects. These focused on quantifying performance in attention and memory, and their underlying neurophysiological processes. In addition, the subjects completed questionnaires about their sense of presence and basic demographic information.

The psychological measures made were:

- Psychological attention task. This is similar to the auditory continuous performance test (Seidman et al., 1998). During the task the subject must react, as soon as possible, to a specific auditory stimulus (target), with a mouse click, and avoid clicking the mouse when four other auditory stimuli are presented (distractors). The stimuli were automatically randomised by computer, but following the same configuration: 8 targets and 32 distractors (20% target stimuli), and the time between stimuli was 800 ms to 1600 ms. Following presentation of the stimuli, the subjects had 750 ms to react, after which any reaction was considered to be an error; as, of course, was reacting to a distractor. This was undertaken 3 times for each PCW, with 1500 ms between sets. After the test, the reaction times to the target stimuli were measured (Attention-Time metric), as were the number of errors made (Attention-Error metric).
- Psychological memory task. This was similar to the Deese, Roediger and McDermott (DRM) paradigm experiments (Beato & Díez, 2011). During the task, the subject had to memorise lists of words associated with a concept that was not presented as a specific word. This task was configured with 15 words, with a similar recall rate (Alonso et al., 2004), presented orally through Loquendo TTS 7 (www.loquendo.com). The subject first had to listen to the words, and then repeat them inside a maximum time of 30 seconds, before moving on to the next list. This was undertaken 3 times for each PCW, so 9 counterbalanced lists were chosen (3 lists x 3 PCWs viewed by each subject). After the test, the number of words the subjects remembered was quantified, and corrected based on the recall rate reported by Alonso et al. (2004) for each word (Memory-Correct answers metric).
- Presence. Sense of presence is the illusion of "being there" (Steuer, 1992) evoked by an environmental simulation. To quantify sense of presence the subjects completed the SUS questionnaire (Slater et al., 1994), which consists of six items evaluated on

a Likert-type scale, from 1 to 7. The objective was to verify that the simulations could be considered satisfactory. The questionnaire was administered after each PCW viewing (SUS-Total metric).

The neurophysiological measures made were:

- Electroencephalogram (EEG). The electroencephalogram recordings were made using the b-Alert x10 device (www.advancedbrainmonitoring.com). The raw signal, sampled at 256 Hz, was pre-processed and analysed using the EEGLAB toolbox (Delorme & Makeig, 2004). The pre-processing was carried out in two stages: (1) signal conditioning; and (2) identification of artefacts. The signal conditioning involved: (1) elimination of the baseline by subtracting the mean value; (2) filtering between 0.5 and 40 Hz (Gudmundsson et al., 2007); and (3) locating corrupted electrodes, that is, those with flat signals for more than 10% of their duration, or if the kurtosis of the electrode reached a threshold of 5 standard deviations of the kurtosis of all the electrodes (Delorme et al., 2001). Thereafter, the signal was split into one-second epochs. The identification of artefacts involved: (1) locating corrupt epochs, that is, those whose kurtosis reached the same threshold as on the electrode scale; (2) automatic locating, eliminating epochs that reached a threshold of 100μV, or a gradient of 70μV, between epochs; and (3) application of independent component analysis (ICA) (Hyvärinen & Oja, 2000), rejecting components related to artefacts. A spectral classification analysis was performed, using the Welch method, to calculate the selected metrics of the pre-processed signals.

  Two EEG metrics were calculated: the relative power (to reduce data variability between subjects; Knyazev et al., 2004) of the beta band (13-30 Hz) of the C3 electrode, which is associated with increased attention (Egner & Gruzelier, 2011; Fuchs et al., 2003); and the highbeta band (21-30 Hz), which is associated with alertness (Marzbani et al., 2016), of electrode CZ, which is associated with enhanced cognitive performance (Vernon et al., 2003). These provided the EEG-C3-Beta and EEG-CZ-Highbeta metrics.

- Heart rate variability (HRV). The electrocardiogram signal was recorded also using the b-Alert x10 device. The raw signal, sampled at 256 Hz, was pre-processed and analysed using the HRVAS toolbox (v.2014-03-21). Pre-processing consisted of (1) detecting the R-points by means of the Pan-Tompkins algorithm (Pan & Tompkins, 1985) and (2) visual diagnosis of ectopic beats and their corrections, and the elimination of excessively noisy intervals. The analysis processed the interbeat intervals in the time-frequency domain, using the Welch method.

  One HRV metric was calculated, that is, HRV-LFHF. This is the ratio between the low frequency, or LF, (0.05 to 0.15 Hz), and the high frequency, or HF, (0.15 to 0.4 Hz) of the signals. As LF is related to sympathetic activity and HF to parasympathetic, HRV-LFHF has been used as an indicator of the balance between sympathetic and parasympathetic activity (Malliani, 1999). In relation to cognitive processes, a relationship has been found between HRV and attentional control (Ramírez et al., 2015).

The neurophysiological metrics were all normalised based on the values obtained for the baselines ($M_{PVW\#x} = (M_{PVW\#x} - |M_{PVW\#BASELINE}|) \, / \, SD_{PVW\#BASELINE}$).

Statistical Analysis

Once the database was anonymised, appropriate statistical analyses were undertaken to address the three study questions. Table 1 describes the analyses, statistical treatments, and expected results. IBM SPSS (v.17.0; www.ibm.com/products/spss-statistics) software was used.

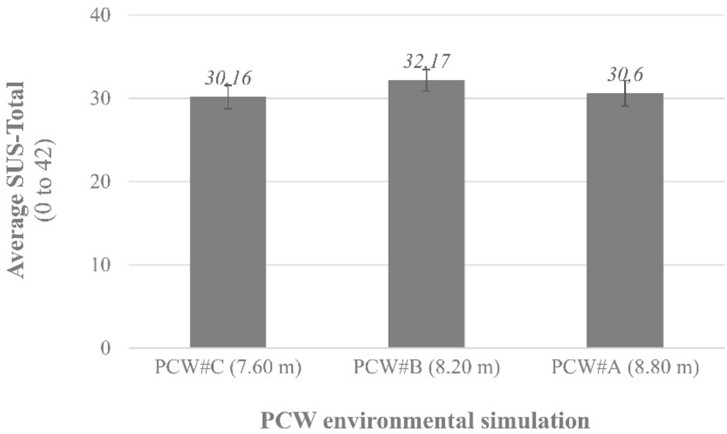
PHASE	ANALYSIS AND DATA USED	STATISTICAL TREATMENT	EXPECTED RESULT
Phase 1.0 "Validation of the VR environment"	Analysis of level of sense of presence. • SUS-Total.	Descriptive analysis of means.	Sufficient level of presence.
Phase 1.1 "Psychological metrics"	Analysis of attention and memory performance • Attention-Time • Attention-Errors • Memory-Correct answers	ANOVA and Bonferroni's post hoc analysis (normally distributed data) for Attention-Time and Memory-Correct answers. Kruskal-Wallis test and Mann Whitney's post hoc analysis (non-normally distributed data) for Attention-Errors.	Significant differences in the psychological metrics based on classroom width. Identification of the PCWs with the best and worst attention and memory performance.
Phase 1.2 "Neuropsychological metrics"	Analysis of the neurophysiological processes related to attention and memory performance. • HRV-LFHF • EEG-C3-Beta • EEG-CZ-Highbeta	Kruskal-Wallis test and Mann Whitney's post hoc analysis (non-normally distributed data) for the three neuropsychological metrics.	Significant differences in the neuropsychological metrics based on classroom width. Identification of the PCWs with the highest and lowest neuropsychological activity.
Phase 1.3 "Correlation between psychological and neurophysiological metrics"	Analysis of the relation between both types of response. • Attention-Time • Attention-Errors • Memory-Correct answers • HRV-LFHF • EEG-C3-Beta • EEG-CZ-Highbeta	Spearman.	Correlation between the psychological task and the neurophysiological responses

Results

The statistical analysis of the data produced the following results.

Phase 1.0: Validation of the VR environment

The average levels of sense of presence per subject (based on the SUS questionnaire) for each PCW were obtained (Figure 5). These levels were considered sufficient, taking into account the results obtained by studies which used similar technologies (Slater & Steed, 2000). Thus, the VR simulations were judged to be satisfactory.



Phase 1.1 Psychological metrics

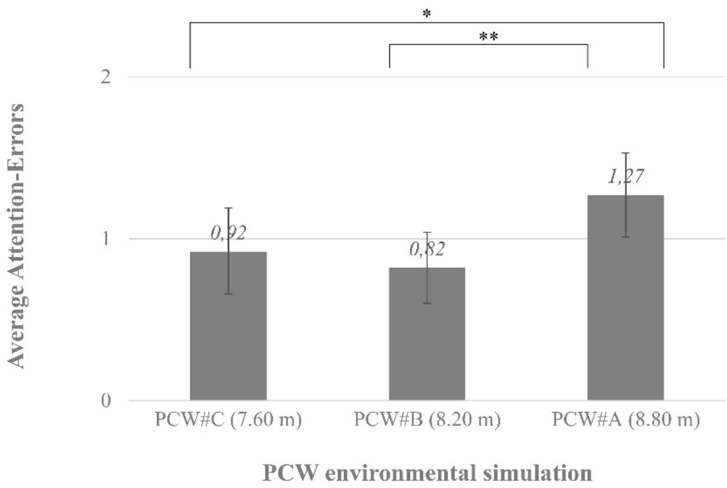
Once the VR environment was validated, the psychological responses were studied through an analysis of the attention and memory performance metrics. The statistical analyses applied were based on the normality of the data, which was examined using the Kolmogorov-Smirnov (K-S) test.

Attention-Time metric

This metric quantifies the reaction time to the target stimuli in the psychological attention task. The greater it is, the worse was the attention performance. Due to the normality of the data (K-S, $p > 0.05$), an ANOVA was applied. This test showed that there are were no significant differences in the reaction times in the attention task based on classroom width ($p=0.359$).

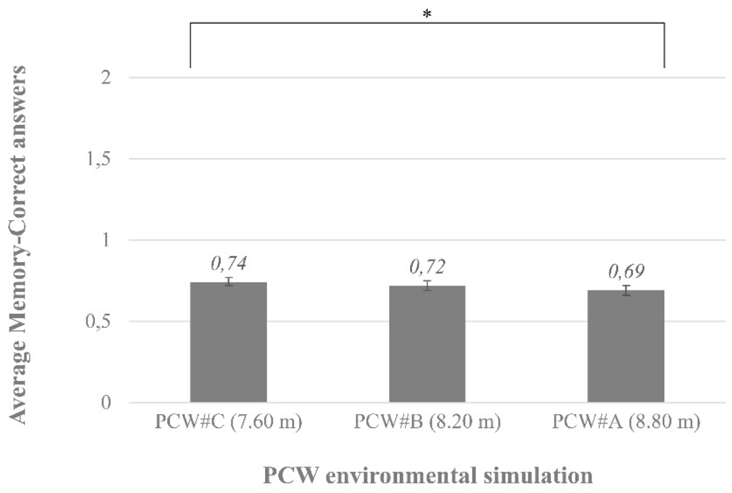
Attention-Errors metric

This metric quantifies the number of errors made in the psychological attention task (reactions with 750+ ms delay to a target stimulus or reacting to a distractor). The greater it is, the worse was attention performance. Due to the non-normality of this data (K-S, $p < 0.05$), a Kruskal-Wallis test was applied. This test showed significant differences in the number of errors made based on classroom width (p= 0.011). A Mann Whitney post hoc analysis showed that this difference occurred between the widest parameter setting (PCW # 01), which produced the worst results, and the other two widths: PCW#02 (p=0.006) and PCW#03 (p= 0.017). There were no significant differences between the two narrowest classroom widths. Figure 6 depicts these results; they suggest a possible U effect.



Memory-Correct answers metric

This metric quantifies the number of words remembered in the psychological memory task. The higher it is, the better was the memory performance. Due to the normality of this data (K-S, p> 0.05), an ANOVA was applied. This test showed significant differences in the number of words recalled based on classroom width (p= 0.050). A Bonferroni's post-hoc test showed that these differences occurred between the greatest (PCW # 01) and the smallest width parameterisations (PCW # 03) (p = 0.048); that is, the narrowest classroom produced the best results. Figure 7, which depicts these results, suggests that performance declines as width increases.

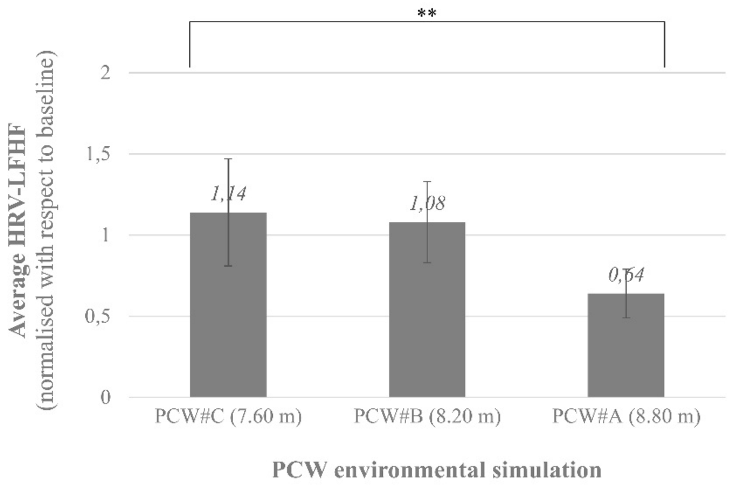


Phase 1.2: Neurophysiological metrics

To complement the psychological metrics, the neurophysiological responses were examined. The HRV-LFHF, EEG-C3-Beta, and the EEG-CZ-Highbeta metrics were analysed; these were selected because they are related to the cognitive processes of memory and attention.

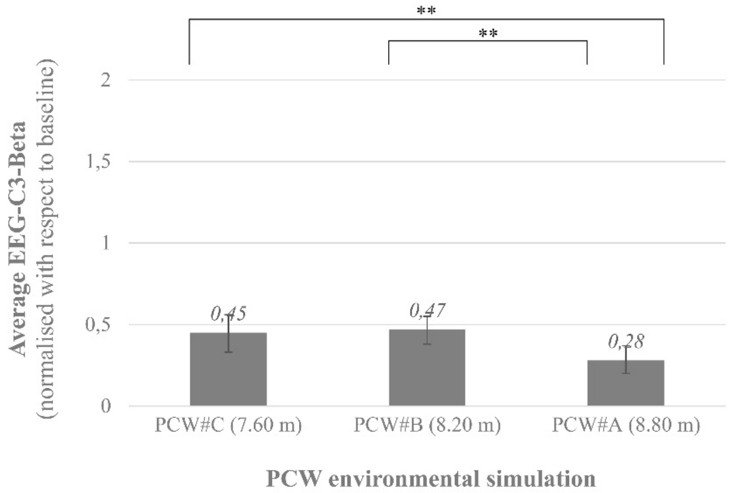
HRV-LFHF metric

This metric is related to the balance of sympathetic activity over parasympathetic activity, and attentional control. Higher values are associated with greater sympathetic system activation. The Kruskal-Wallis test showed significant differences in the HRV-LFHF metric based on classroom width (p= 0.017). The Mann Whitney post hoc analysis showed that this difference occurred between the greatest (PCW # 01) and the smallest width parameterisations (PCW # 03) (p = 0.004). Figure 8 depicts these results, showing the metric decreases with increasing width.



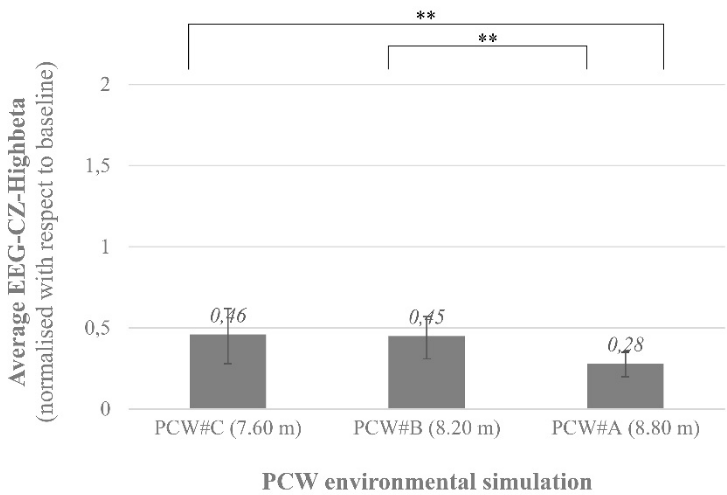
EEG-C3-Beta metric

This metric is related to increased thinking and focusing. Higher values are associated with greater attentional levels. The Kruskal-Wallis test showed significant differences in the EEG-C3-Beta based on classroom width (p = 0.000). The Mann Whitney post hoc analysis showed that this difference occurred between the widest parameterisation (PCW # 01), which generates the highest values in this metric, and the other two widths, PCW # 02 (p = 0.000) and PCW # 03 (p = 0.001). Figure 9 depicts these results; they suggest that from some point equal to, or greater than, the intermediate width (8.20 m), the metric is greatly reduced.



EEG-CZ-Highbeta metric

This metric is related to increased alertness. Higher values are associated with higher cognitive performance. The Kruskal-Wallis test showed significant differences in the EEG-CZ-Highbeta metric based on classroom width ($p = 0.003$). The Mann Whitney post hoc analysis showed that this difference occurred between the greatest width parameterisation (PCW # 01) and the other two widths, PCW # 02 ($p = 0.003$) and PCW # 03 ($p = 0.004$). Figure 10 depicts these results; the neurophysiological metric values decrease as width increases.



Phase 1.3: Correlation between psychological and neurophysiological metrics

Finally, the correlation between the psychological (Attention-Time, Attention-Errors, and Memory-Correct answers) and the neurophysiological (HRV-LFHF, EEG-C3-Beta, and EEG-CZ-Highbeta) metrics is presented at Table 2. The Spearman correlation coefficient confirmed the existence of significant relationships.

NEUROPHYSIOLOGICAL RESPONSES		ATTENTION PERFORMANCE		MEMORY PERFORMANCE
		Attention-Time	Attention-Errors	Memory-Correct answers
HRV-HF	Correlation Coef.	-0.074	0.072	0.232
	Sig.	0.356	0.370	0.004
EEG-C3-Beta	Correlation Coef.	.-0.167	-0.313	0.297
	Sig.	0.026	0.000	0.000

EEG-CZ-Highbeta	Correlation Coef.	-0.261	-0.223	0.044
	Sig.	0.000	0.003	0.558

In attentional performance a significant relationship was found between the EEG metrics EEG-C3-Beta and EEG-CZ-Highbeta, and the psychological attention task metrics Attention-Time and Attention-Errors. This relationship is inverse, so higher EEG values are associated with lower reaction times and fewer errors; that is, higher attentional performance.

In memory performance a significant and positive relationship was found between the Memory-Correct answers metric and the HRV-LFHF and EEG-C3-Beta metrics. Thus, higher neurophysiological metric values were associated with higher memory performance.

Discussion

Attention and memory, as cognitive functions, constitute a very important field of work within neuropsychological research (Bernabéu, 2017); attentional and memory processes are involved in the activation of other cognitive processes such as creativity, which is considered to be essential in 21st century teaching-learning, and is postulated as a basic skill for adapting to a modern world in continuous and rapid transformation. In addition, as the experiment was conducted using VR, the results could have interesting implications for online teaching and, in the future, for the design of physical classrooms.

The findings showed the influence of classroom width on memory and attention. This can be discussed at methodological and results' levels.

At the methodological level, it is worth highlighting: (1) the use of virtual reality; and (2) the compatibility of the virtual reality and neurophysiological recording systems.

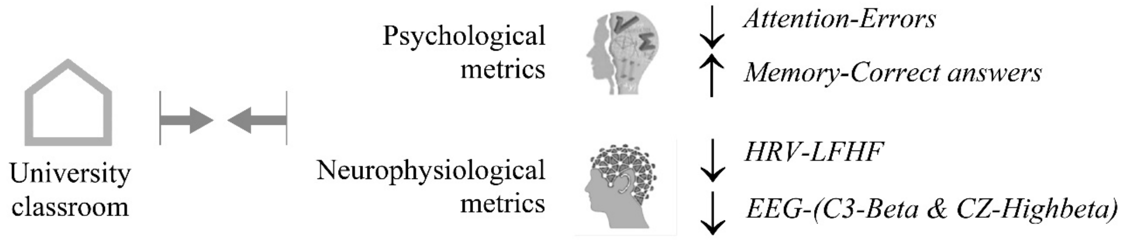
The present study, among others, underlines the usefulness of virtual reality for studying the effects of architectural design variables on human users. VR represents an advance as it allows variables under study to be isolated and closely controlled, minimising costs. It should be borne in mind that the majority of works that have assessed the effect of teaching environments on students' cognitive functions have been carried out in real spaces (Cheryan et al., 2014; Guardino & Fullerton, 2010; Yang et al., 2013; Yildirim et al., 2011), which creates a need to work with large samples of classrooms. As environmental simulation tools can generate similar user responses to those generated by the physical environments they represent (Higuera-Trujillo et al., 2017), they are an important contribution to the architectural design field.

The compatibility of the assessment and simulation systems is a significant methodological synergy. Recording variations in neurophysiological, as well as psychological, responses to virtual spaces which have been modified in a controlled way, provides a new level of knowledge in the exploration of the bases that underlie design issues. Thus, several authors have used virtual classrooms to measure students' cognitive functions (Cho et al., 2002; Nolin et al., 2016). However, a combination of both systems has not, hitherto, been used to study the cognitive effects of the design variables of teaching spaces.

As to the results of the present study, worth highlighting are: (1) the psychological effects; (2) the neurophysiological effects; and (3) the correlation between the psychological and the neurophysiological metrics.

First, significant differences, based on width, in the results of both the psychological attention and memory metrics were identified (Figure 11). In general, wider classrooms were seen to be associated with poorer results, both in the terms of the errors made in the attention test (Attention-Time) and in the memory task (Memory-Correct answers).

Although, to the best of the authors' knowledge, no previous studies have analysed the specific effects of classroom width, there is a bibliography on the effects of other geometric variables, such as classroom height. Read et al. (1999) suggested that ceiling height affects children's cooperative behaviour, and Ahrentzen and Evans (1984) found that classrooms with higher ceilings generate greater satisfaction. Similarly, in the commercial context it has been found that low ceilings and narrow aisles enhance attention and increase subjects' concentration on the attributes of displayed products (Levav & Zhu, 2009; Meyers-Levy & Zhu, 2007). These results are in line as with those of the present study, which suggests that narrower spaces are associated with higher performance in attention and memory tasks.



Second, significant differences in the results of the neurophysiological metrics of some of the attention and memory processes were observed (Figure 11). The HRV and EEG metrics reduced as classroom width increased. Each metric had its own particularities, but overall they seem to be associated with an increase in arousal levels, so it may be that wider classrooms cause lower arousal. This is in line with studies that have indicated that an appropriate level of arousal improves cognitive performance (Yerkes & Dodson, 1908). It is difficult, however, to compare these results with those of previous works, since very few studies have analysed the influence of geometric variables on neurophysiological responses. Furthermore, although in another context, Vartanian et al., (2015) analysed, using fMRI, the effect of ceiling height on the activation of certain brain regions, but achieved no conclusive results. However, Erkan (2018) provided evidence that ceiling height does have a positive effect on subjects' cognitive and behavioural responses; the present results are consistent with this finding.

Third, the psychological and neurophysiological metrics were seen to be correlated. In attention, the two psychological metrics, Attention-Time and Attention-Errors, correlated significantly with the two EEG metrics, EEG-C3-beta, and EEG-CZ-Highbeta. In fact, this relationship was observed with classroom width modifications: that is, as classroom width increased, the EEG metrics decreased (Figures 9 and 10), and attentional performance declined (Figure 6). Memory performance was significantly correlated with HRV-LFHF and EEG-C3-Beta. The same trend is shown in the graphs: width increases are associated with a reduction in both neurophysiological metrics (Figures 8 and 9) and memory performance (Figure 7). Thus, greater classroom width may generate less arousal, thus negatively affecting attention and memory performance. The EEG results seem to be consistent with other works which have shown that beta band metric increases are associated with higher attention levels (Gola et al., 2013; Ko et al., 2017), and when undertaking challenging information processing activities (Geske, 2005; Horst, 1987). The HRV results were consistent with works that have found a relationship between increases in HRV activity and better performances in attention and memory (Burg et al., 2012; Hansen et al., 2003) and learning (Shah et al., 2011). These correlations are interesting, given that neurophysiological measurements offer some advantages over traditional measurement systems, in that they allow data to be recorded in real time, and with less bias, and provide no opportunity for manipulation by the subject (Riedl et al., 2014).

The study has three main limitations. First, the possibility of unexplored synergistic effects among the design variables was not addressed. The analysis starts from a standard classroom format to which a set of design variations was applied. This certainly represents a limitation as, although all the variables, except classroom width, remained unchanged, there could be hidden effects among the many design variables that converge in real physical spaces (and, therefore, in the base classroom). Therefore, it would be interesting to replicate the analysis in other classrooms to check if these results remain the same when other design variables are modified, and to analyse the joint effect of combinations of variables. Second, more sophistication could be introduced by increasing the number of viewing points. Future studies might examine the effects of using different viewpoints, for example, the differential effects of sitting close to the blackboard, and half way between the board and the back of the room, and at the back of the room, and of sitting to the left, centre and right of the room. Third, the presence of other students may have a considerable influence on performance. In the present study it was decided to omit this factor due to parameterisation difficulties (e.g., including different types and intensity of distracting actions). It would be interesting to address this issue in future studies.

Conclusions

The results suggest that narrower university classrooms enhance attention and memory performance, which are associated with higher arousal levels. However, future studies will be necessary to identify the dimensions below which performance is reduced. In this regard, the neurophysiological metrics studied (HRV-LFHF, EEG-C3-beta, and EEG-CZ-Highbeta) could be useful due to the correlations found with the psychological metrics related to performance in attention and memory (Attention-Time, Attention-Errors, and Memory-Correct answers). In summary, this study presents findings that may be useful for a variety of readerships, including researchers, building design professionals, and lecturers. For researchers, the present study demonstrates that a combination of tools (virtual reality and psychoneurophysiological recordings) is effective for the study, and design, of university classrooms. This is an opportunity for more comprehensive studies into different design variables (not only geometric, but also colour, lighting, etc.) focused on improving students' cognitive processes. The guidelines set out in the present study can help building professionals create improved designs that would complement current technical regulations. For example, by extending the methodology of this study to identify the specific inflexion points where performance declines/improves could provide designers with data to develop more versatile classrooms; this could be translated into public policies. For lecturers, the guidelines can help them choose appropriate classrooms for their lessons, and even to adapt their teaching methods. Similarly, both the methodology and the results may be helpful in the design and definition of virtual learning environments.

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Figure captions

Figure 1. General outline of the methodology.

Figure 2. PCW simulations and plans (the dot indicates the position of the subject).

Figure 3. Subjects during the classroom experiment.

Figure 4. General experimental sequence.

Figure 5. Average level of presence for each PCW.

Figure 6. Average levels of the Attention-Errors metric as a function of classroom width. The brackets indicate the comparisons and the asterisks the significance levels (*p < 0.05, **p < 0.01).

Figure 7. Average levels of the Memory-Correct answers metric as a function of classroom width. The bracket indicates the comparison and the asterisk the significance level (*p < 0.05, **p < 0.01).

Figure 8. Average levels of the HRV-LFHF metric as a function of classroom width. The bracket indicates the comparison and the asterisks the significance level (*p < 0.05, **p < 0.01).

Figure 9. Average levels of the EEG-C3-Beta metric as a function of classroom width. The brackets indicate the comparisons and the asterisks the significance levels (*p < 0.05, **p < 0.01).

Figure 10. Average levels of the EEG-CZ-Highbeta metric as a function of classroom width. The brackets indicate the comparisons and the asterisks the significance levels (*p < 0.05, **p < 0.01).

Figure 11. Summary of the effects of classroom width reduction on psychological (attention and memory) and neurophysiological (HRV and EEG) metrics.

Table captions

Table 1. Statistical treatments.

Table 2. Spearman correlation between the psychological and neurophysiological metrics.