Cold and warm coloured classrooms. Effects on students' attention and memory measured through psychological and neurophysiological responses.

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Abstract

Mounting evidence indicates that the colour hue of classroom walls influences student performance. However, the effect of this design parameter has not hitherto been simultaneously assessed for two key cognitive learning functions of attention and memory. The objective of the present study is to analyse the impact that warm and cold hue coloured classroom walls have on the cognitive attention and memory functions of university students. To this end, the attention and memory performance of 160 participants was evaluated in 12 warm and 12 cold hue colour settings in a virtual classroom. Their performance was quantified through psychological (attention and memory tasks) and neurophysiological (heart rate variability and electroencephalogram) metrics related to the cognitive functions analysed. The results showed that cold hue colours increase arousal and improve performance in attention and memory tasks; and design guidelines can be established. Furthermore, correlations were observed between the psychological and neurophysiological metrics, which represents an important advance in the neuroarchitecture discipline. The variety of implications of the results makes this work useful for architectural design professionals, researchers, and policymakers working on improving learning spaces.

Keywords: classroom colours; attention; memory; psychological responses; neurophysiological responses; neuroarchitecture

Abbreviations:

- Virtual reality: VR.
- Head-mounted display: HMD.
- Electroencephalogram: EEG.
- Heart rate variability: HRV.

1. Introduction

There is evidence that the colours of architectural environments have physiological, emotional, and cognitive impacts on students [1–4]. In fact, three environmental factors that impact on students' academic progress have been identified: (1) level of stimulation, (2) individualisation, and (3) naturalness [5]; it has been shown that colour has a significant weight in the level of stimulation, which explains 23% of the influence of the environment on academic progress [5]. Level of stimulation could be related to arousal, which some authors have identified as influencing the performance of activities. Arousal has been used to explain, for example, that certain hues (green and blue versus red) in physical spaces are associated with increased physical strength [6] and improved performance in motor activities (green) [7]. The optimal levels of arousal for task performance, however, are not yet a matter of consensus. On the one hand, some authors have argued that the influence of colours on arousal levels follows a curvilinear relationship, based on the Yerkes-Dodson principle [8]; thus, the optimum solution is to use intermediate colour levels in architectural spaces [9]. On the other hand, other authors have argued that the best academic performance is achieved when students reach a state of telic motivation, during which they are focused on achieving a goal; this state is associated with low arousal [10], for which short-wavelength colours, cold hue colours, are recommended [11]. In any case, it is clear that colour choice is important. In addition to its effects on performance, a suitable choice of colour in the learning environment is important for reducing visual fatigue, improving users' orientation [12], supporting development processes [13], and facilitating cooperative behaviour among students [12].

Within the guidelines it could be noted that white spaces may produce poorer performance. Despite the fact that neutral colours dominate in most educational facilities [14], these spaces have been associated with a 25% drop in human efficiency [15], and an increase in 22% in distraction [16]. Hence, these colours may not be the best option. In this sense, it has been shown that coloured spaces are associated with the committing of fewer errors in proofreading tasks [17], and higher task execution speeds [18]. In general, it can be stated that light colours have been shown to best correlate with learning progress [5]. However, discrepancies are seen to arise in specific teaching contexts. For example, Mahnke [19] recommended cold hue colours for high/secondary school classrooms, while Barret [20] suggested that warm hue colours are more appropriate for senior grades, and that cold hue colours are more appropriate for junior grades.

This recommendation is consistent with recent studies that have suggested that classrooms with cold-hued, low-saturated colours on the walls (light blue), are perceived more positively by school-age students than classrooms with warm-hued, low-saturated walls (cream or pink) [21].

However, the subjective perception of both performance and well-being does not always coincide with greater efficiency in the performance of cognitive activities. For example, the hues (blue and yellow) that students believe convey the most positive emotional states are not associated with the best reading comprehension results [22]. This outcome does not seem to be limited to this specific case; similar contradictions have been found in the emotional states and performance of participants provoked by room colour [3]. Therefore, although mood state can be determinant in explaining some of the effects of colour (e.g., in creativity, [3]), the conclusions of studies on colour preferences cannot be directly extrapolated to the objective of identifying the possible effects of colour on task performance.

Within this objective, the bibliography evidences a series of recurring issues: (1) exposure time; (2) task difficulty; and (3) task type. Regarding exposure time, it has been found that results may differ based on how long subjects are exposed to colours [9]. Thus, for example, Ainsworth [23] found no significant differences in typing performance based on room colour hues (cold vs warm), and similarly Kwallek [17] found no significant differences in proofreading tasks for short periods of 20 minutes, but found differences for longer periods of 1 hour. As to task difficulty, there is evidence that performance in very difficult tasks is higher in blue environments than in red, and performance in easy tasks is higher in red rooms than in blue [24]. Which, returning to the relationship of arousal with performance, could be interpreted as meaning that more cognitively complex tasks require less arousal to reach optimal performance [25]. As to the third issue, task type, colour might significantly affect the performance of some tasks -such as mental rotation- but not of others, such as numerical reasoning, visual memory, cued recognition of categories, and cued recognition of word pairs [26]. This concept makes it possible to reconcile apparently discordant results. Among these are that red environments favour performance in detail-oriented tasks, while blue environments favour creative tasks [27]. In this sense, there is a limitation in that, although performance in attention [28] and creativity [3] have been widely studied, memory has received less attention [26], despite it playing a fundamental role in the learning process. It is also worth noting that, combining the second two issues (task difficulty and task type), it has been possible to demonstrate that “red enhanced the performance on a simple detail-oriented task. However, blue improved the performance in a difficult detail-oriented task as well as in both simple and difficult creative tasks” [29]. Taking these points into account, it can be seen that the influence of the colour hue of architectural spaces on task performance is complex, with results that can often seem contradictory. This problem is based, in part, on context and the approaches taken to quantify performance.

First, the context used in most studies that have compared the influence of cold and warm hues on performance has often been limited by the difficulty of working with physical spaces. Using physical spaces has the restriction of limiting the number of colours employed (if the same classroom is used), or the restriction of the inability to isolate the colour from other environmental variables that may influence the results (if different classrooms are used). Furthermore, it is well known that the appearance of a surface’s colour depends on the relative positions of the light source and the observer [30], difficult to control in a physical space. Thus, experiments have been carried out using adapted study tables [22,26], laboratory spaces converted into offices [3], and real classrooms of heterogeneous typology [5]. On other occasions, conclusions about the use of colour have come from studies carried out without considering the characteristics of the surrounding architectural spaces. For example, changing the colours of the foregrounds and backgrounds of evaluation materials [29,31–34]. Taking these issues into account, virtual reality (VR) tools provide many advantages. VR offers the possibility of simulating spaces under sustainable and economical laboratory conditions, having found that, in general, these simulations generate psychological and neurophysiological responses similar to the physical environments represented [35]. Which has been validated for the execution of tasks in the specific case of university classrooms [36]. By using VR, the range of warm and cold hue colours can be studied more thoroughly. In addition, simulation systems allow researchers to control other variables such as noise, time, and distractions. These capabilities have led some authors to argue that simulation systems offer better predictive information about performance in real environments [37]. In fact, many studies have shown the utility of virtual classrooms for assessing children with ADHD [38,39]. However, VR has been very little used in studies whose objective is to improve design based on the measurement of participants' responses [40].

Second, some studies have made use only of self-report or psychological tasks, which are insufficient to quantify cognitive-emotional states, which involve both psychological and neurophysiological responses [41]. The capability of recording neurophysiological responses is especially important as the influence of colour on learning performance goes beyond conscious control [27,32,42], and unconscious responses are more objective than self-reporting. [43]. Despite this, few studies on the effects of hue have recorded subjects' neurophysiological measures (for a review, see [44]). As an exception, the study by Küller et al. [3], which included electroencephalogram (EEG) and heart rate variability (HRV) metrics, should be highlighted. Among their conclusions, they found that red spaces are associated with lower delta rhythms, so they are more arousing than blue spaces; and that red spaces decrease heart rate, perhaps as a compensatory response to visual over-stimulation. Thus, the incorporation of neurophysiological recording tools enriches the quantification of cognitive-emotional functions.

Taking into account the above aspects, the objective of this paper is to analyse the impact that cold- and warm-hued colours have on the attention and memory of university students. Three questions are posed: (1) Do the cold or warm hues of classroom walls influence the attention and/or memory performance of students? (2) Do the cold or warm hues of classroom walls influence attention- and/or memory-related neurophysiological responses? And (3) is there a correlation between performance in attention and/or memory and the neurophysiological measures obtained?

2. Materials and methods

A laboratory study was undertaken to address the study objective. Different parameterisations of wall hues (PHW) were shown to experimental subjects in a VR setting, and their effects on the subjects' attention and memory were quantified through psychological and neurophysiological responses. The analysis, undertaken in three phases, focused directly on the three questions into which the study objective is divided: (1) an analysis of attention and memory performance based on colour hue, measured through psychological responses; (2) an analysis of the underlying cognitive processes, based on colour hue, measured through neurophysiological responses; and (3) an analysis of the correlation between the psychological and neurophysiological responses. In addition, prior to the analyses, the VR environment was validated through level of sense of presence. Figure 1 depicts the general methodological outline.

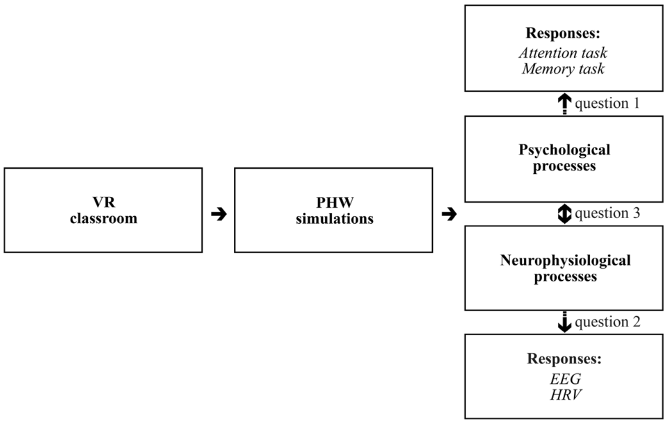

Figure 1. General methodological outline. [Single-column fitting image; grayscale image]

2.1. Colour selection

In the Munsell notation system colours are described by their hue, value, and chroma. Hue corresponds to the dominant wavelength of the physical stimulus; value is the lightness or darkness of a colour; and chroma is the saturation, vividness, or intensity, of the perceived colour [45]. For expample, the colour 5GY 5/4 in Munsell notation corresponds to: 5GY = hue (green yellow), 5 = value, 4 = chroma. The colour hue is the perceptual attribute that allows the perceiver to distinguish between cold and warm colours, following Itten's chromatic circle [46].

The colours were chosen with this in mind. They were based on a combination of colours with different hues and chromas: 8 different hues uniformly distributed on the colour wheel (4 cold: 5GY, 5BG, 5PB, 5P; and 4 warm: 5RP, 5R, 5YR, 5Y); configured with two different chromas (which always had a distance of 6 Munsell chroma units between them). The value remained constant in an intermediate level: 5. The 16 colours chosen were: 5GY 5/4, 5GY 5/10, 5BG 5/4, 5BG 5/10, 5PB 5/8, 5PB 5/14, 5P 5/6, 5P 5/12, 5RP 5/8, 5RP 5/14, 5R 5/10, 5R 5/16, 5YR 5/4, 5YR 5/10, 5Y 5/2, and 5Y 5/8. These colours were displayed in 16 monochromatic classroom configurations, in which frontal and lateral wall colours remained the same. In addition, we included 8 scenes (combinations #3, 6, 9, 12, 15, 18, 21 and 24) with two colours belonging to the same hue but with different chroma: frontal walls (with smaller surfaces) with higher chroma; and lateral walls (with larger surfaces) with lower chroma. This resulted in 24 (16 + 8) total combinations. Figure 2 describes the 24 configurations. In this regard, it should be noted that, as the colours were viewed on the digital screen of the VR system, the original Munsell colours were translated into RGB notation (using the ColorMunki TM application (www.colormunki.com) to be rendered on the surfaces. It was checked that this colour was achieved at the same point in each image (the centre of the wall over the blackboard). So, although the illumination influences the appreciation of the colour, the study was strictly conducted presenting the chosen colours. As can be seen, the cold hue colours (purple, bluish-purple, blue, bluish-green, green, yellowish-green) are close to blue, while the warm hue colours (yellow, yellow-orange, orange, red-orange, red, red-violet) are close to red [47].

COMBINATION	FRONTAL WALL			LATERAL WALL		
	MUNSELL NOTATION	RGB COLOUR	COLD/ WARM	MUNSELL NOTATION	RGB COLOUR	COLD/ WARM
#01	5GY 5/4	114,127,82	COLD	5GY 5/4	114,127,82	COLD
#02	5GY 5/10	105,131,30	COLD	5GY 5/10	105,131,30	COLD
#03	5GY 5/10	105,131,30	COLD	5GY 5/4	114,127,82	COLD
#04	5BG 5/4	81,129,142	COLD	5BG 5/4	81,129,142	COLD
#05	5BG 5/10	48,132,154	COLD	5BG 5/10	48,132,154	COLD
#06	5BG 5/10	48,132,154	COLD	5BG 5/4	81,129,142	COLD
#07	5PB 5/8	84,123,176	COLD	5PB 5/8	84,123,176	COLD
#08	5PB 5/14	40,124,204	COLD	5PB 5/14	40,124,204	COLD
#09	5PB 5/14	40,124,204	COLD	5PB 5/8	84,123,176	COLD
#010	5P 5/6	138,112,153	COLD	5P 5/6	138,112,153	COLD
#011	5P 5/12	155,99,182	COLD	5P 5/12	155,99,182	COLD
#012	5P 5/12	155,99,182	COLD	5P 5/6	138,112,153	COLD
#013	5RP 5/8	175,98,128	WARM	5RP 5/8	175,98,128	WARM
#014	5RP 5/14	138,112,153	WARM	5RP 5/14	138,112,153	WARM
#015	5RP 5/14	138,112,153	WARM	5RP 5/8	175,98,128	WARM
#016	5R 5/10	196,88,88	WARM	5R 5/10	196,88,88	WARM
#017	5R 5/16	231,49,69	WARM	5R 5/16	231,49,69	WARM
#018	5R 5/16	231,49,69	WARM	5R 5/10	196,88,88	WARM
#019	5YR 5/4	152,114,89	WARM	5YR 5/4	152,114,89	WARM
#020	5YR 5/10	182,101,32	WARM	5YR 5/10	182,101,32	WARM
#021	5YR 5/10	182,101,32	WARM	5YR 5/4	152,114,89	WARM
#022	5Y 5/2	129,121,98	WARM	5Y 5/2	129,121,98	WARM
#023	5Y 5/8	144,120,35	WARM	5Y 5/8	144,120,35	WARM
#024	5Y 5/8	144,120,35	WARM	5Y 5/2	129,121,98	WARM

Figure 2. Description of the configurations of the selected colours. [2-column fitting image; colour image online only]

2.2. Stimuli

A classroom at the Polytechnic University of Valencia was virtualised. The classroom was chosen under the criterion it was representative of physical university teaching spaces. The classroom, in the Higher Technical School of Building Engineering, measures 16.50 x 8.80 x 3.80 metres. The 24 colour configurations (12 warm and 12 cold), defined in the previous sub-section, were applied to the base virtualisation. This resulted in the 24 PHWs shown in Figure 3 (the distortion of these images is due to the 2D display of 3D environments; the vision through the virtual reality device was natural).

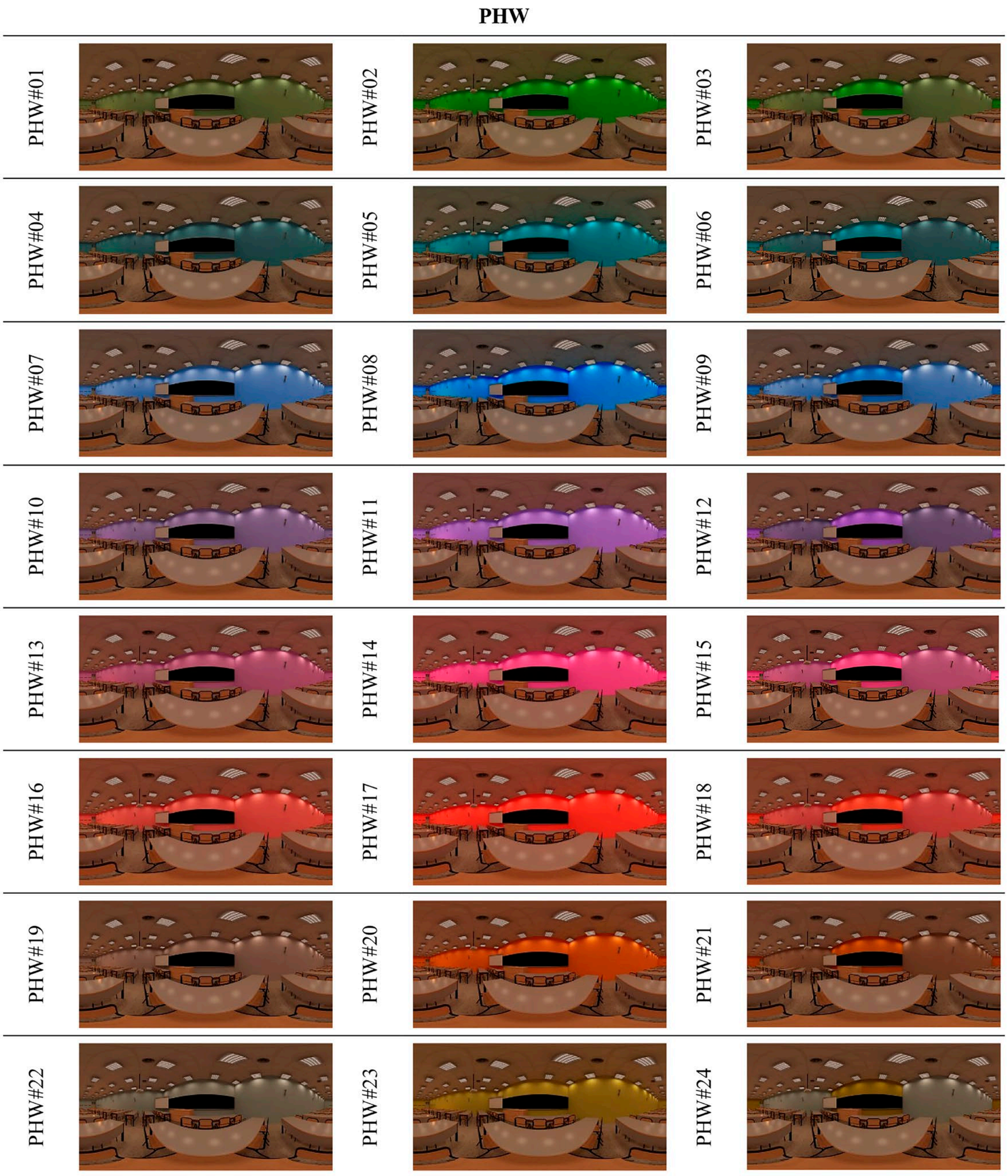

Figure 3. PHW simulations. [2-column fitting image; colour image online only]

2.3. Environmental simulation set-ups

The participants used a head-mounted display (HMD) to visualise the PHWs. All research was carried out in the same laboratory and in the same time slots, taking care to maintain silence and temperature. Some aspects related to the device and the environmental simulation should be highlighted.

The HMD device used was the HTC Vive (www.vive.com). The HTC Vive provides a total resolution of 2160 × 1200 pixels (1080 × 1200 per eye), with a refresh rate of 90Hz, and a field of view of 110º. The device was calibrated prior to the experiment to ensure the consistency of the colours rendered. Figure 3 shows participants taking part in the experiment.

The simulations were developed through a process of modelling and rendering. The three-dimensional model was constructed using Rhinoceros (v.5.0; www.rhino3d.com). The rendering of the different PHWs was performed on the 3D model using the Corona Renderer engine (v.2.0; https://corona-renderer.com). The same point of view was taken in each case, that of a student sitting in the middle of the second row of tables. From this point, an adequate impression of the whole space was obtained during all the experiment. Regarding lighting, the Correlated Colour Temperature (CCT) in creating the virtual space was a simulation of 4,000 Kelvin, a light close to a F-9 standard lighting. The virtual implementation was undertaken using Unity3D (v5.6; www.unity3d.com).

Figure 4. Participants during the classroom experiment. [Single-column fitting image; colour image online only]

2.4. Participants

A total of 160 subjects participated in the experiment: 57% male, 43% female, average age 23.56 years (σ = 3.433). Four inclusion criteria were established: (1) being a university student; (2) to be aged between 18 to 23 years; (3) to have been born and be resident in Spain (to avoid cultural effects); and (4) having normal or corrected-to-normal vision with contact lenses (to avoid the problems that can be caused by using spectacles with the HMD). Each participant visualised three PHWs, based on an incomplete counterbalanced randomisation. This allowed each PHW to be viewed by 20 participants. The study was executed in accordance with the Declaration of Helsinki, and the experimental methodology was approved by the Review Board of the Institute for Research and Innovation in Bioengineering (Project BIA2017-86157-R). Figure 5 describes the general experimental sequence.

	CONCEPT	TIME (MINUTES)	
Preparation	**PARTICIPANT INITIATION** Reception, basic instructions, signing of consent form, fitting of neurophysiological recording devices.	≈10	↓
	SCREENING FOR COLOUR-VISION DEFICIENCIES Farnsworth-Munsell Dichotomous D-15 Test	≈5	
	TEST SCENARIO Viewing a test scenario to adjust the environmental simulation device and acclimatise the participant.	≈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 it 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	→#1→#2→#3 (Figure 3, counterbalanced)
	CLASSROOM EXPERIMENT Environmental simulation of the assigned PHW. Metrics: Neurophysiological recordings (HRV-nLF; HRV-nHF; EEG-C3-Beta; EEG-CZ-Beta; EEG-F3-Highbeta; EEG-FZ-Highbeta).	1.5	
	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	↓
	PARTICIPANT EXIT PROTOCOL Retrieval of the devices, accompany participant to the exit.	≈5	
	TOTAL:	**60**	

Figure 5. General experimental sequence. [2-column fitting image; grayscale image]

2.5. Data analysis

Psychological and neurophysiological responses were obtained from all the participants. These focused on quantifying performance in attention and memory and their underlying neurophysiological processes. In addition, the participants completed questionnaires about their sense of presence during the PHW experiment.

The psychological measures were:

- Presence. Sense of presence is the illusion of "being there" [48], evoked by an environmental simulation that is not perceived as synthetic. To quantify sense of presence the subjects completed the SUS questionnaire [49], which consists of six items evaluated on a Likert-type scale, from 1 to 7; with a maximum score of 42 (6 items x 7). The objective was to verify that the simulations could be considered satisfactory. A high level of presence can be considered when the items have a score of more than 4 [50], which is equivalent to a score of 24. The questionnaire was administered after each PHW visualization (SUS-Total).
- Psychological attention task. This is similar to the auditory continuous performance test [51]. The participant had to react to a specific stimulus (target) as soon as possible with a mouse click, and avoid clicking the mouse when other stimuli appeared (four different distractors). The configuration parameters of the task were: (a) auditory stimuli, reproduced by the PC; (b) 20% target stimuli (8 target and 32 distractors); (c) 800 ms - 1600 ms time between stimuli; and (d) 750 ms to react to the stimuli (after which any reaction was considered an error, similar to reacting to a distractor). This was repeated 3 times for each PHW, with a break of 2000 ms between sets. After the test the number of errors made and the reaction time to the target stimuli (Attention-Errors and Attention-Time metrics) were quantified.
- Psychological memory task. This was similar to the Deese, Roediger and McDermott (DRM) paradigm experiments [52]. During the task, the subject had to memorise lists of words associated with a concept that was not presented as a specific word. The configuration parameters of the task were: (a) auditory stimuli, reproduced through the PC, using Loquendo TTS 7 (www.loquendo.com); (b) 15 words, with a similar recall rate [53]; (c) 30 seconds to repeat the lists, before advancing to the next list. This was repeated 3 times for each PHW (9 lists per participant: 3 lists x 3 PHWs, which were counterbalanced), with a break of 2,000 ms between sets. After the test, the number of words remembered was quantified, with corrections being made based on the recall rate reported by [52] for each word (Memory-Correct answers metric).

The neurophysiological measures were:

- Heart rate variability (HRV). HRV measures variations in the intervals between heartbeats [54]. This was measured using the b-Alert x10 device (www.advancedbrainmonitoring.com). The raw signal, sampled at 256 Hz, was pre-processed and analysed using the HRVAS toolbox (v. 2014-03-21). Two HRV metrics were obtained [55]: the low-frequency band of the signal (0.05 to 0.15 Hz), which is related to sympathetic activity and may involve an increase in arousal (HRV-nLF metric); and the high-frequency band of the signal (0.15 to 0.4 Hz), which is related to parasympathetic activity and may involve a decrease in arousal (HRV-nHF metric). Both were expressed in normalised units [56]. In relation to cognitive processes, it should be noted that HRV is related to attentional control.
- Electroencephalogram (EEG). An EEG measures variations in the electrical activity of the surface of the scalp [57]. This measurement was also made using the b-Alert x10 device. The raw signal, sampled at 256 Hz, was pre-processed and analysed using the EEGLAB toolbox [58]. Four EEG metrics were calculated; the metrics were based on the relative power of each band with respect to the total signal, because this method has been seen to reduce differences between subjects [59]: the beta band (13-30 Hz) of the C3 and CZ electrodes (EEG-C3-Beta and EEG-CZ-Beta metrics), which are associated with increased attention [60,61] and cognitive performance [62]; and the highbeta band (21-30 Hz) which, in general, is associated with alertness [63], of the F3 and FZ electrodes (EEG-F3-Highbeta, and EEG-CZ-Highbeta metrics), which can be indicators of working memory and attention judgment, respectively [64]. The four EEG metrics were normalised based on the values obtained for the baselines ($M_{PHW\#x} = (M_{PHW\#x} - |M_{PHW\#BASELINE}|) / SD_{PHW\#BASELINE}$).

All the neurophysiological measures were recorded during the 90 seconds following the preparation audio, and prior to the attention and memory tasks. This is based on the fact that after this time frame, with similar simulation systems, an increase in arousal can be generated and recorded at a neurophysiological level [40]; which could distort the results.

2.6. Statistical Analysis

The data collected, both through psychological and neurophysiological responses, were anonymised; thereafter, they were used to carry out the appropriate statistical analyses to explore the study questions (Table 1). IBM SPSS software (v.17.0; www.ibm.com/products/spss-statistics) was used.

PHASE	ANALYSIS AND DATA USED	STATISTICAL TREATMENT	EXPECTED RESULT
Phase 1.0 Validation of the VR PHW	Analysis of level of sense of presence. • SUS-Total.	Descriptive analysis of means.	Sufficient level of presence.
Phase 1.1 Analysis of psychological responses	Analyses of attention and memory performance. • Attention-Time • Attention-Errors • Memory-Correct answers	Mann Whitney's test (non-normally distributed data) for Attention-Time and Attention-Errors. ANOVA (normally distributed data) for Memory-Correct answers.	Significant differences in the psychological responses, based on the warm or cold hue of the classroom. Identification of the PHWs which gave the best and worst attention and memory performance.
Phase 1.2 Analysis of neuropsychological responses	Analysis of the neurophysiological processes related to attention and memory performance. • HRV-nLF • HRV-nHF • EEG-C3-Beta • EEG-CZ-Beta • EEG-F3-Highbeta • EEG-FZ-Highbeta	Mann Whitney test (non-normally distributed data) for the six neuropsychological responses.	Significant differences in the neuropsychological responses, based on the warm or cold hue of the classroom. Identification of the PHWs with the highest and lowest neuropsychological activity.
Phase 1.3 Correlation between psychological and neurophysiological responses	Analysis of the relation between both types of responses. • Attention-Time • Attention-Errors • Memory-Correct answers • HRV-nLF • HRV-nHF • EEG-C3-Beta • EEG-CZ-Beta • EEG-F3-Highbeta • EEG-FZ-Highbeta	Spearman.	Correlation between the psychological and the neurophysiological responses

Table 1. Statistical treatments.

3. Results

The statistical analysis of the psychological and neurophysiological responses provided the following results.

3.1. Phase 1.1 Validation of the VR PHW

Average levels of sense of presence per participant (based on the SUS questionnaire) were obtained for each PHW (Figure 6). These results were considered sufficient as all the simulations reached scores close to or above 24 points [50], so the VR PHW simulations can be regarded as satisfactory at this level.

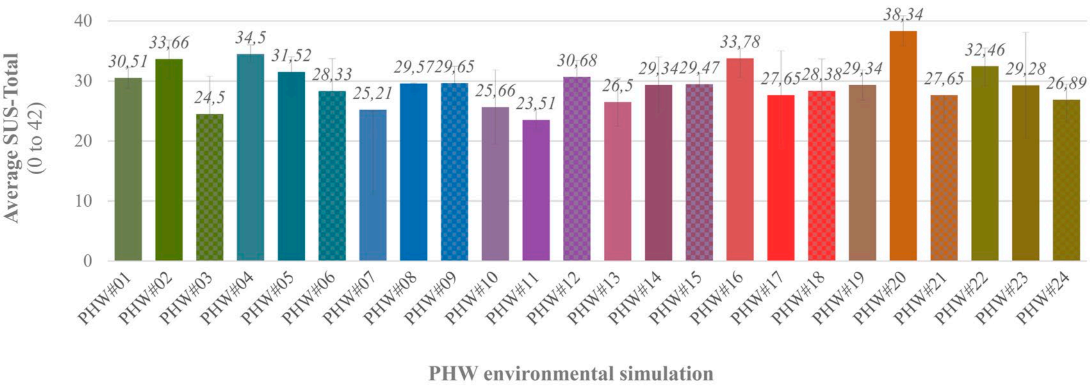

Figure 6. Average level of sense of presence for each PHW. [2-column fitting image; colour image online only]

3.2. Phase 1.2 Analysis of the psychological responses

The attention and memory tasks were analysed at the psychological level. The statistical analyses applied were based on the normality of the data for each metric, which were assessed using the Kolmogorov-Smirnov (K-S) test.

3.2.1. Psychological attention task

The psychological attention task used two metrics, Attention-Time and Attention-Errors. Attention-Time measures average reaction times; the shorter the time, the higher the attention performance. Due to the normality of the data (K-S, $p > 0.05$), the comparison between both groups (warm and cold hues) for this variable was made through an ANOVA. Figure 7a presents the mean reaction times for each group. The ANOVA test did not identify significant differences in reaction time when the classroom hues were modified ($p = 0.531$). Attention-Errors quantifies the number of errors made; the less errors made, the higher the attention performance. Due to the non-normality of the data (K-S, $p <0.05$,), the Mann Whitney test was used for the comparison. The Mann Whitney test identified significant differences between the groups ($p = 0.008$), the performance being higher in cold-hued PHWs (Figure 7b).

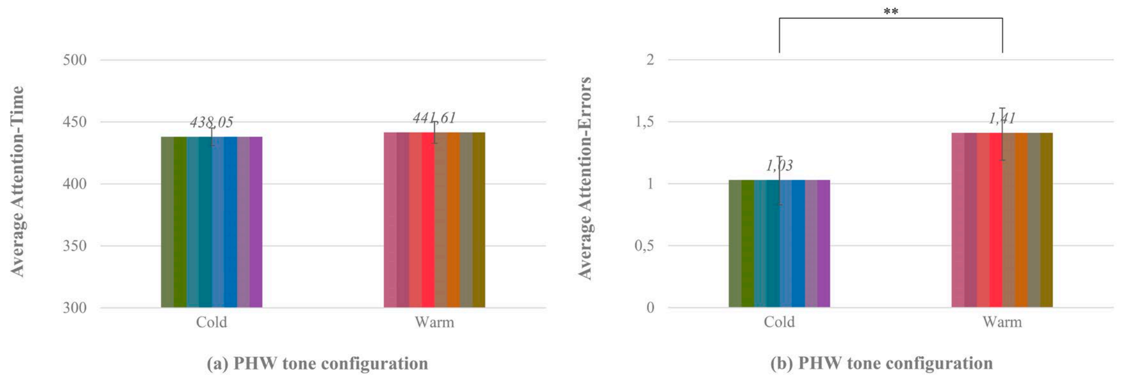

Figure 7. Results of the psychological attention task: Attention-Time (7a) and Attention-Errors (7b). The bracket indicates the comparison and the asterisks the significance level (*$p < 0.05$, **$p < 0.01$). [2-column fitting image; colour image online only]

3.2.2. Psychological memory task

The psychological memory task used the Memory-Correct answers metric. This metric quantifies the number of words remembered in the psychological memory task. The more words remembered, the higher the memory performance. Due to the normality of this data (K-S, $p> 0.05$), an ANOVA was applied. The ANOVA identified that there were significant differences based on the hue (warm or cold) of the classrooms ($p = 0.000$), with memory performance being higher in cold-hued PHWs (Figure 8).

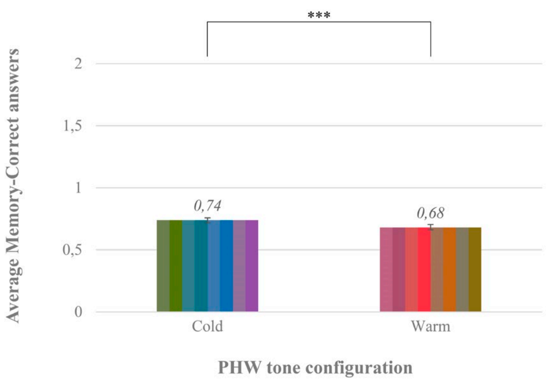

Figure 8. Results of the psychological memory task, Memory-Correct answers. The bracket indicates the comparison and the asterisks the significance level (*p < 0.05, **p < 0.01).

[Single-column fitting image; colour image online only]

3.3. Phase 1.3 Analysis of the neurophysiological responses

The HRV and EEG metrics were analysed at the neurophysiological level. The Kolmogorov-Smirnov (KS) test indicated that the data followed a non-normal distribution, so the Mann Whitney test was used to compare the six neuropsychological metrics to verify the existence of significant differences between the warm-hued and cold-hued PHWs.

3.3.1. HRV

HRV was assessed through two metrics, HRV-nLF and HRV-nHF. The first quantifies sympathetic activity and the second parasympathetic. The Mann Whitney test identified that there were significant differences based on the hue (warm or cold) of the classrooms both for HRV-nLF ($p = 0.010$; Figure 9a) and HRV-nHF ($p = 0.022$; Figure 9b). The results showed that cold-hued PHWs generated greater sympathetic activity and less parasympathetic activity, thus they are associated with an increase in arousal.

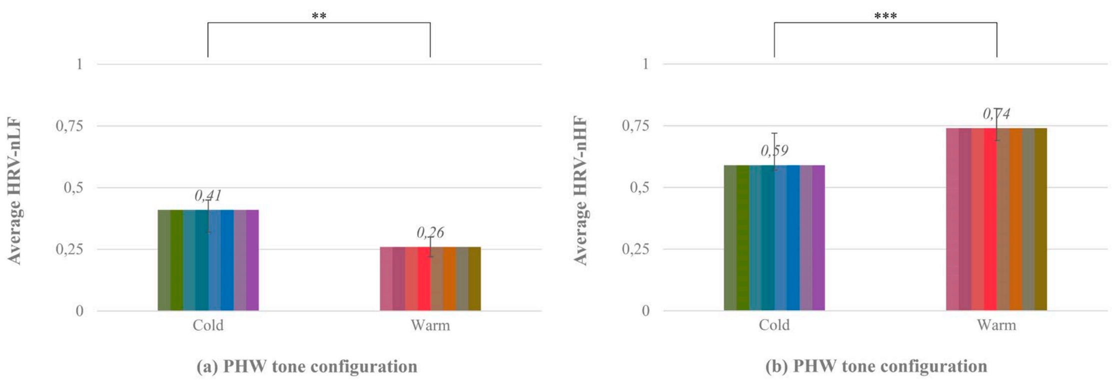

Figure 9. Results of the HRV measures, HRV-nLF (9a) and HRV-nHF (9b). The brackets indicate the comparisons and the asterisks the significance levels (*p < 0.05, **p < 0.01). [2-column fitting image; colour image online only]

3.3.2. EEG

The EEG recordings used two beta band-based metrics and two highbeta band-based metrics.

The beta band metrics used were EEG-C3-Beta and EEG-CZ-Beta; these are related, respectively, to increased attention and cognitive performance. The Mann Whitney test identified that there were significant differences based on classroom hue (warm or cold hues) for both EEG-C3-Beta ($p = 0.026$; Figure 10a) and EEG-CZ-Beta ($p = 0.009$; Figure 10b), suggesting that cold-hued PHWs contribute to the achievement of higher levels of attention and cognitive performance.

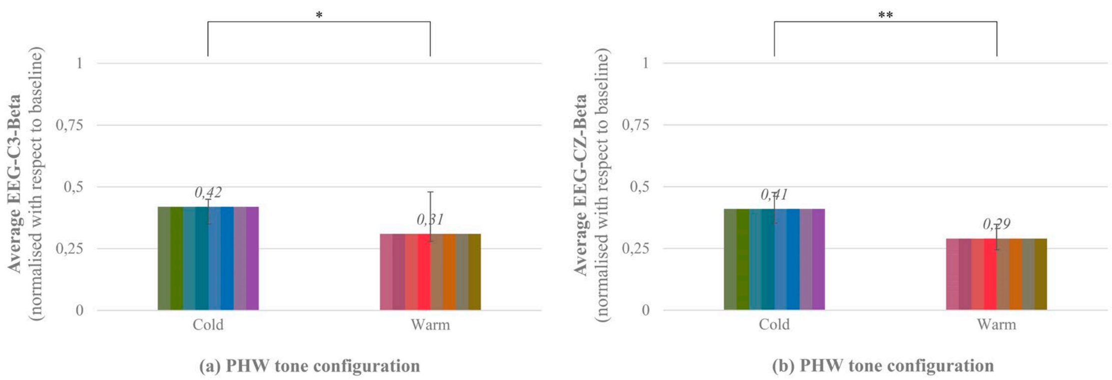

Figure 10. Results of the beta band EEG metrics: EEG-C3-Beta (10a) and EEG-CZ-Beta (10b). The brackets indicate the comparisons and the asterisks the significance levels (*p < 0.05, **p < 0.01). [2-column fitting image; colour image online only]

The highbeta band metrics used were EEG-F3-Highbeta and EEG-FZ-Highbeta. These may be related to an increase in alertness that improves, respectively, working memory and attention judgment. The Mann Whitney test identified significant differences both in the EEG-F3-Highbeta ($p = 0.008$; Figure 11a) and in the EEG-FZ-Highbeta ($p = 0.033$; Figure 11b) metrics based on classroom hue (warm or cold). This suggests that cold-hued PHWs contribute to the achievement of higher levels of working memory and attention.

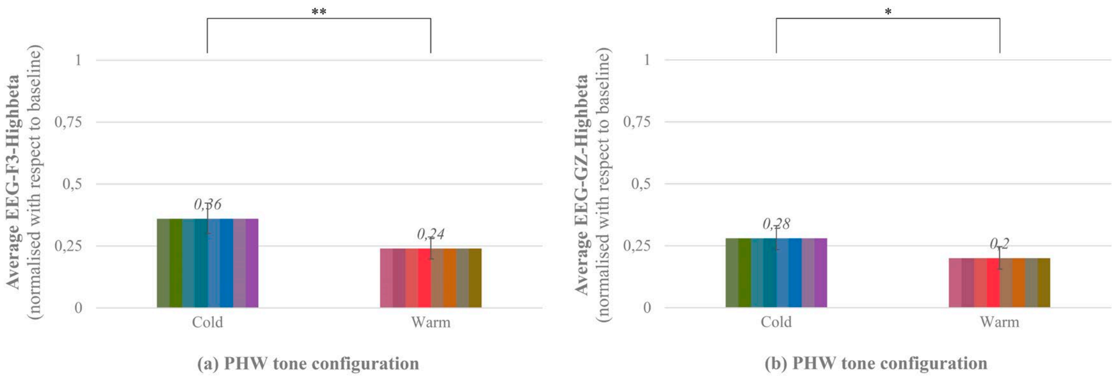

Figure 11. Results of the highbeta band EEG metrics, EEG-F3-Highbeta (11a) and EEG-FZ-Highbeta (11b). The brackets indicate the comparisons and the asterisks the significance levels (*$p < 0.05$, **$p < 0.01$). [2-column fitting image; colour image online only]

3.4. Phase 1.4 Correlation between the psychological and the neurophysiological responses

The correlations between the psychological metrics (Attention-Time, Attention-Errors, Memory-Correct answers) and the neurophysiological metrics (HRV-nLF, HRV-nHF, EEG-C3-Beta, EEG-CZ-Beta, EEG-F3-Highbeta, EEG-FZ-Highbeta) were analysed by applying the Spearman correlation coefficient (Table 2). With respect to the task of attention, a negative and significant correlation is obtained between the errors made and all the metrics ($p<0.05$) (except HF of HRV). The metric with the highest correlation is LF of HRV, which can be interpreted as a small-to-moderate correlation [65]. In the case of reaction time, the highest correlation (also a small-to-moderate correlation) is obtained with the beta metric. Regarding the memory task, a small significant and positive correlation is obtained with LF of HRV.

NEUROPHYSIOLOGICAL RESPONSES		ATTENTION PERFORMANCE		MEMORY PERFORMANCE
		Attention-Time	Attention-Errors	Memory-Correct answers
HRV-nLF	Correlation Coef.	-0.031	-0.347	0.192
	Sig.	0.724	0.000	0.025
HRV-nHF	Correlation Coef.	-0.023	0.003	0.020
	Sig.	0.776	0.974	0.805
EEG-C3-Beta	Correlation Coef.	-0.306	-0.193	0.094
	Sig.	0.000	0.013	0.228
EEG-CZ-Beta	Correlation Coef.	-0.334	-0.186	0.084
	Sig.	0.000	0.017	0.281
EEG-F3-Highbeta	Correlation Coef.	-0.136	-0.211	0.106
	Sig.	0.082	0.007	0.174
EEG-FZ-Highbeta	Correlation Coef.	-0.185	-0.258	0.105
	Sig.	0.018	0.001	0.180

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

4. Discussion

This paper analyses the impact that the warm and cold hue colours of classroom walls have on the cognitive functions of attention and memory of university students. The study's main contribution is the identification of a strong effect of hues on performance at different levels. This is important as previous studies have not found this influence on performance [66], or have suggested that its influence might be weaker than other environmental variables [5]. The findings will be discussed in relation to the methodology and the results. The limitations of the study will also be discussed.

At the methodological level, two important inclusions should be highlighted: (1) the neurophysiological measurements; and (2) the VR. On the one hand, neurophysiological measurements are important as they provide more objective information than self-reports [43]. In the present study, this has made it possible to obtain complementary information; this complementary assessment has scarcely been undertaken in studies with similar objectives [44]. On the other hand, VR facilitates control of the environmental variables under study, and is compatible with the psychological and neurophysiological assessments of the participants [67]. VR allowed the use of a relatively wide range of stimuli (24 configurations, 12 warm-hued and

12 cold-hued), which gives greater generalisability and applicability to the results. These two tools made it possible to enhance the robustness of the results.

At the results level, four aspects should be highlighted: (1) the psychological attention task results; (2) the psychological memory task results; (3) the neurophysiological results; and (4) the correlations between the psychological metrics of attention and memory and the neurophysiological metrics.

In the first place, at the psychological attention task results level, it was observed that cold-hued colours (between yellowish green and purple, 5GY, 5BG, 5PB, and 5P) were associated with higher performance. Specifically, fewer errors were committed in the attention task (Attention-Time). This result disagrees with studies that found no differences in tasks such as reading [22] and typing [23] performance. However, it is consistent with studies that found increased concentration in high/secondary school students due to the effect of cold hues [19], and that found that blue hues helped more than red hues in the performance of particularly difficult tasks [24], and in the achievement of higher IQ test scores [31–33]. Authors interpret these different influences of colour on performance following two lines of research: motivation and arousal, which are linked to the type of task and difficulty of the task respectively [8, 32]. More recently, authors have been effective trying to study these two interpretations together and reported that red enhanced performance on a simple detail-oriented task while blue improved performance on a difficult detail-oriented task as well as on creative tasks, no matter whether the task was simple or difficult [29]. The present study supports these findings, given that the attention tasks used bear a certain relationship to tasks used to test individuals' attention to detail, and creative tasks. Furthermore, interestingly, blue has been reported to facilitate students' study activities in a university residence [68]; however, as previously noted, actual performance and self-reported opinion about performance do not always coincide.

Second, the psychological memory task performance results are consistent with the attention results: cold-hued coloured classroom walls were associated with better results in the memory task (Memory-Correct answers). This result is especially noteworthy, given that most studies have focused on attention performance, and few on memory performance [26]. This finding is partially consistent with other research that has shown that cold lighting is associated with higher performance in long-term memory tasks [69]. Therefore, guidelines for using cold-hued colours would be valid for improving both memory and attention performance.

Third, the HRV and EEG neurophysiological results indicated that cold-hued colours elicited significantly higher activation. This result contradicts some other studies. HRV measurements have shown, for example, that warm hues have arousal properties that make participants feel more active [22,70,71]. However, other authors have reported lower activation in red environments due to a compensatory phenomenon that addresses over-stimulation [3]. EEG-based studies have identified that red environments provoke greater activation in the frontal area [32], and generate greater arousal than blue, as evidenced by lower delta band values, which is related to sleep [3], or delays in cortical habituation responses [72]. However, some authors have suggested that there is insufficient EEG-based evidence to argue that warm-hued colours are more arousing than cold-hued [73]. Thus, although warm hue colours are generally associated with higher neurophysiological activation, the literature is not conclusive in this regard. Furthermore, the metrics used in this article are not exclusively focused on arousal, but attempt also to explore underlying issues related to the cognitive functions of attention and memory.

Fourth, interesting correlations were found between task performance and the neurophysiological metrics. Regarding HRV, a small-to-moderate link was found between activation of the sympathetic system (HRV-nLF metric) and errors in the attention task (Attention-Errors). Regarding EEG, a small-to-moderate correlation is also observed between the beta band and the reaction times of the attention task (Attention-Time) and between highbeta band and the errors made (Attention-Errors). This relationship is in line with earlier studies that showed that the cognitive, physiological, and affective effects of the physical environment on learning are closely interconnected [74]. In fact, there is current growing interest in obtaining objective real-time data from participants while they are being exposed to different stimuli [75]; to achieve this it is necessary to integrate the relevant neurophysiological, technological, and design processes [76].

The present study, thus, advances the identification of candidate biological metrics to examine the cognitive processes of attention and memory.

Finally, regarding the limitations of the present study, two aspect should be emphasised. On the one hand, the experimental methodology was specifically designed to examine the differences between two colour groups, cold- and warm- hued. General results were pursued, that is, not specific to each hue, for which a larger sample would be necessary. Consequently, judging by the results obtained, it would be interesting to conduct future studies that focus on exploring each hue, in detail, at the psychological and neurophysiological levels. On the other hand, having chosen only one point of view within the classroom (the middle of the second row of tables) might have included a position-related effect. An experimental approach with different positions could have reduce this, but would have required a larger sample of participants, or not studying as many colour combinations. In this sense, future studies could address which positions within the classroom benefit most from the colour changes in the classroom.

5. Conclusions

The present study explores the impact of the cold and warm hue colours of the walls of university classrooms on the cognitive functions of attention and memory. This impact was addressed through the combined use of VR (which allowed a wide colour range to be explored) and psychological (which allowed performance to be quantified) and neurophysiological (which allowed related cognitive processes to be explored) metrics. Both the psychological and neurophysiological results indicated that cold hues enhanced performance in attention and memory more than did warm hues. This can be explained at the neurophysiological level by the achievement of a level of sympathetic system activation appropriate to the maintenance of higher alertness and cognitive performance. In this regard, it is worth highlighting the correlation between the psychological metrics and most of the neurophysiological metrics, which suggests that it would be useful to use the latter (HRV-nLF, EEG-C3-Beta, EEG-CZ-Beta, EEG-F3-Highbeta, and EEG-FZ-Highbeta) to understand the underlying processes in memory and attention in greater detail. The results of the present study can be useful for a wide range of professionals involved in the design of, and research into, teaching spaces.

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