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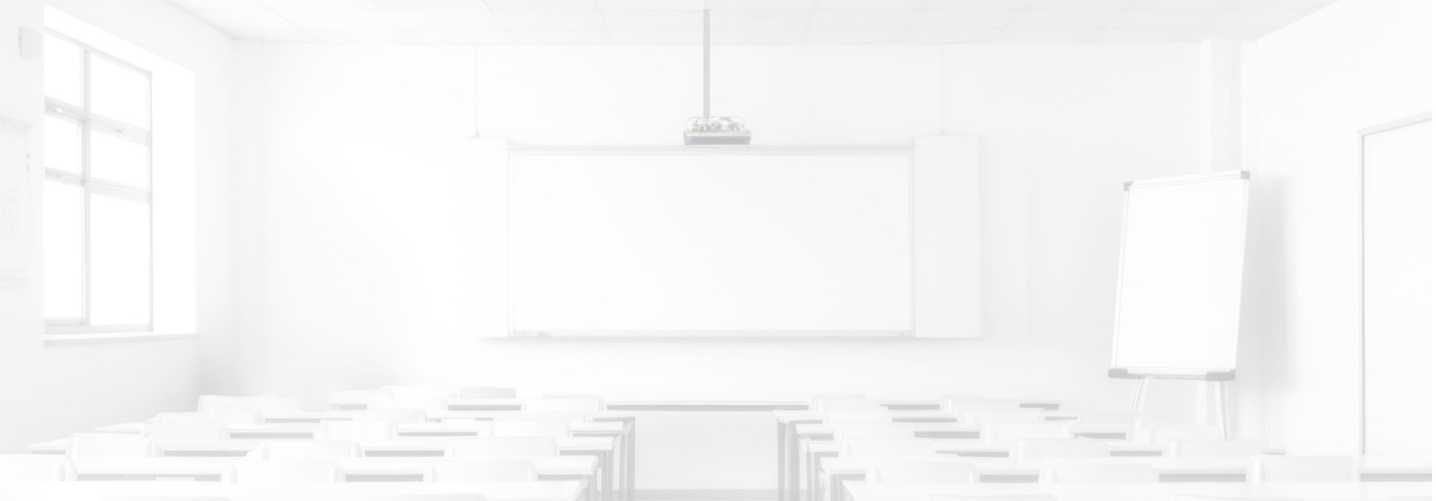

# EL DISEÑO DEL AULA COMO FACILITADOR DEL APRENDIZAJE: **EL PAPEL DE LA LUZ, EL COLOR Y LA DIMENSIÓN EN LOS PROCESOS COGNITIVOS**

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Mayo, 2024

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# CLASSROOM DESIGN AS A FACILITATOR OF LEARNING: THE ROLE OF **LIGHT, COLOR,** AND **DIMENSION** IN COGNITIVE PROCESSES

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*La verdad es que este proceso no ha sido tan duro como hubiera podido ser. Y eso no es porque yo sea una superhéroe, sino porque me he rodeado de superhéroes.*

*Quienes me conocen saben que nunca me ha costado mostrar mis emociones: reír, llorar, enfadar... Tampoco nunca me ha costado expresar lo que siento, ni pedir perdón ni, mucho menos, agradecer.*

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# Resumen

*"No debemos olvidar que la arquitectura se construye para vivir en ella y no para mirarla".* Con estas palabras, el arquitecto Van Der Rohe enfatiza la importancia de que el diseño arquitectónico esté al servicio de la vida y contribuya a mejorarla. Esta visión evidencia la conexión significativa entre la psicología y la arquitectura, ya que los espacios que habitamos determinan nuestro desarrollo personal. De esta forma, cada entorno tiene una finalidad principal y debe ser funcional para ello. En particular, los entornos educativos desempeñan un papel fundamental en el proceso de enseñanza-aprendizaje. Por lo tanto, es crucial diseñar estos espacios no solo para que sean agradables para sus ocupantes, sino también para potenciar los procesos cognitivos implicados en la educación, asegurando así un ambiente propicio para el aprendizaje y el crecimiento personal. De acuerdo a ello, el objetivo de la presente tesis doctoral es analizar la relación entre tres elementos de diseño del aula (luz, color y dimensión) y tres procesos cognitivos de los estudiantes (memoria, atención y la percepción de preferencia por el entorno).

Para su abordaje, se llevaron a cabo tres estudios en laboratorio. Estos estudios consistieron en la evaluación cognitiva de cada participante mientras se encontraban inmersos en aulas virtuales que diferían únicamente en los tres elementos de diseño objeto de estudio, replicando así un entorno real pero con variaciones controladas. Para ello, se hizo uso de dos instrumentos concretos compatibles entre sí y de gran aporte al ámbito de la arquitectura: 1) la realidad virtual

como herramienta de visualización de espacios y 2) el desempeño de tareas específicas de atención, memoria y preferencia como herramientas de medición de la cognición del sujeto. En el primer estudio se analizó el efecto de las intervenciones de diseño (en cuanto a luz, color y dimensión) en el rendimiento de atención y memoria y en la preferencia del alumnado, analizando el impacto relativo de cada una de ellas. Este enfoque comparado permite comprender a qué cambios físicos del aula son más sensibles los diferentes procesos cognitivos del alumnado. El estudio se llevó a cabo en conjunto con los dos géneros y, también, de forma separada. En el segundo estudio, se identificaron los valores concretos de cada uno de los tres elementos de diseño estudiados (luz: iluminancia y temperatura del color; color: tono y saturación; dimensión: altura y anchura) que consiguen mejorar la memoria de hombres y mujeres, minimizando las diferencias entre ambos géneros. Por su parte, el tercer estudio propone un análisis conjunto de los tres elementos de diseño mediante programación lineal multiobjetivo con el objeto de identificar las combinaciones específicas de luz, color y forma que maximizan los beneficios en términos de memoria, atención y preferencia.

Los resultados del primer estudio mostraron que, del conjunto de posibles intervenciones de un aula, la iluminación (frente a las intervenciones en color o dimensión) es el elemento de diseño que más afecta a la cognición del alumnado. Pese a que la cognición de hombres y mujeres difiere en su sensibilidad ante los cambios del diseño, la atención es el proceso cognitivo más sensible. Por su parte, el segundo estudio determinó que la memoria de hombres y mujeres responde de forma diferente ante el conjunto de parámetros de los elementos de diseño del aula estudiados. En este sentido, una temperatura del color de la iluminación de 6500K, el color de paredes azul (Munsell, 5B) con saturación alta y las aulas más anchas, especialmente de 7.2m, pueden plantearse como un diseño que favorece la memoria de los alumnos sin crear diferencias entre géneros. No obstante, la aproximación del tercer estudio puso de relevancia que estos elementos no afectan a todos los procesos cognitivos de manera uniforme y que, además, existe una influencia sinérgica entre dichos elementos. Ello subraya la importancia de estudiar la relación entorno-persona desde una perspectiva holística. De esta forma, el efecto combinado de 100lx, 6500K, 4.4m de alto, 8.4m de ancho, un color 5B o morados (Munsell, 5P/5PB) de saturación baja del aula optimiza la memoria, atención y preferencia de los estudiantes. Además, también se pudo concluir que la misma combinación del color morado con una iluminancia de 300lx, un alto de 3.2m o 4.4m y un ancho de 6m o 8.4m, respectivamente, supone unos niveles de memoria y atención aún más elevados.



Del conjunto de resultados se concluye que los elementos del aula tienen interrelación entre ellos, por lo que deben ser estudiados en su conjunto. A ello se le suma la complejidad del estudiante ya que su cognición no sigue un mismo patrón. Por lo tanto, es necesario estudiar este paradigma en su conjunto. En este sentido, se explora una valiosa metodología que combina herramientas de control del espacio, como la realidad virtual, con herramientas de medición cognitiva, como tareas específicas validadas. El enfoque desarrollado en este trabajo puede ser prometedor ya que supone un comienzo de multidisciplinariedad en el que se unen las dos áreas de conocimiento: arquitectura y psicología. Por ello, es de esperar que el presente trabajo marque un nuevo paso en esa dirección.

La memoria doctoral se presenta en un formato de compendio de artículos, estructurada en ocho capítulos. El primer capítulo introduce y contextualiza el trabajo. El segundo detalla el objetivo general y tres objetivos específicos de la tesis. El tercero describe la metodología utilizada, incluyendo procedimientos, materiales y herramientas. Los capítulos cuatro a seis presentan los artículos de investigación publicados que abordan cada objetivo específico. Cada artículo sigue un formato estándar con introducción, metodología, discusión y conclusiones. El séptimo capítulo analiza globalmente los resultados y sus limitaciones. El octavo capítulo ofrece la conclusión final destacando la contribución significativa de la tesis.

# Resum

*"No hem d'oblidar que l'arquitectura es construeix per a viure-hi i no per a mirar-la"*. Amb aquestes paraules, l'arquitecte Van Der Rohe emfatitza la importància que el disseny arquitectònic estiga al servei de la vida i contribuïsca a millorar-la. Aquesta visió evidencia la connexió significativa entre la psicologia i l'arquitectura, ja que els espais que habitem determinen el nostre desenvolupament personal. D'aquesta manera, cada entorn té una finalitat principal i ha de ser funcional per a això. En particular, els entorns educatius juguen un paper fonamental en el procés d'ensenyament-aprenentatge. Per tant, és crucial dissenyar aquests espais no només perquè siguen agradables per als seus ocupants, sinó també per a potenciar les funcions cognitives implicades en l'educació, assegurant així un ambient propici per a l'aprenentatge i el creixement personal. D'acord amb això, l'objectiu de la present tesi doctoral és analitzar la relació entre tres elements de disseny de l'aula (llum, color i dimensió) i tres funcions cognitives dels estudiants (memòria, atenció i la percepció de preferència per l'entorn).

Per a abordar-ho, es van dur a terme tres estudis en laboratori. Aquests estudis van consistir en l'avaluació cognitiva de cada participant mentre es trobaven immersos en aules virtuals que diferien únicament en els tres elements de disseny objecte d'estudi, replicant així un entorn real però amb variacions controlades. Per a això, es va fer ús de dos instruments concrets compatibles entre si i de gran aportació a l'àmbit de l'arquitectura: 1) la realitat virtual com a eina de visualització d'espais i 2) el desenvolupament de tasques específiques d'atenció,

memòria i preferència com a eines de mesura de la cognició del subjecte. En el primer estudi es va analitzar l'efecte de les intervencions de disseny (quant a llum, color i dimensió) en el rendiment d'atenció i memòria, i en la preferència de l'alumnat, analitzant l'impacte relatiu de cadascuna d'elles. Aquest enfocament comparat permet comprendre a quins canvis físics de l'aula són més sensibles els diferents processos cognitius de l'alumnat. L'estudi es va dur a terme en conjunt amb els dos gèneres i, també de manera separada. En el segon estudi, es van identificar els valors concrets de cadascun dels tres elements de disseny estudiats (llum: il·luminància i temperatura del color; color: to i saturació; dimensió: alçària i amplària) que aconsegueixen millorar la memòria d'homes i dones, minimitzant les diferències entre ambdós gèneres. Per la seua banda, el tercer estudi proposa una anàlisi conjunta dels tres elements de disseny mitjançant programació lineal multiobjectiu amb l'objecte d'identificar les combinacions específiques de llum, color i forma que maximitzen els beneficis en termes de memòria, atenció i preferència.

Els resultats del primer estudi van mostrar que, del conjunt de possibles intervencions d'una aula, la il·luminació (enfront de les intervencions en color o dimensió) és l'element de disseny que més afecta la cognició de l'alumnat. Malgrat que la cognició d'homes i dones difereix en la seua sensibilitat davant els canvis del disseny, l'atenció és la funció cognitiva més sensible. Per la seua banda, el segon estudi va determinar que la memòria d'homes i dones respon de manera diferent davant el conjunt de paràmetres dels elements de disseny de l'aula estudiats. En aquest sentit, una temperatura del color de la il·luminació de 6500K, el color de parets blau (Munsell, 5B) amb saturació alta i les aules més amples, especialment de 7.2m, poden plantejar-se com un disseny que afavoreix la memòria dels alumnes sense crear diferències entre gèneres. No obstant això, l'aproximació del tercer estudi va posar de relleu que aquests elements no afecten a tots els processos cognitius de manera uniforme i que, a més, existeix una influència sinèrgica entre aquests elements. Això subratlla la importància d'estudiar la relació entorn-persona des d'una perspectiva holística. D'aquesta manera, l'efecte combinat de 100lx, 6500K, 4.4m d'alt, 8.4m d'ample, un color blau (Munsell, 5B) o morat (Munsell, 5P/5PB) de saturació baixa de l'aula optimitza la memòria, atenció i preferència dels estudiants. A més, també es va poder concloure que la mateixa combinació del color morat amb una il·luminància de 300lx, una alçària de 3.2m o 4.4m i amplària de 6m o 8.4m, respectivament, suposa uns nivells de memòria i atenció encara més elevats.

Del conjunt de resultats es conclou que els elements de l'aula tenen interrelació entre ells, per la qual cosa ha de ser estudiat en el seu conjunt. A açò s'hi suma la complexitat de l'estudiant ja que la seua cognició no segueix un mateix patró. Per tant, és necessari estudiar aquest paradigma en el seu conjunt. En aquest sentit, s'explora una valuosa metodologia que combina eines de control de l'espai, com la realitat virtual, amb eines de mesurament cognitiu, com tasques específiques validades. L'enfocament desenvolupat en aquest treball pot ser prometedor ja que suposa un començament de multidisciplinarietat en el qual s'uneixen les dues àrees de coneixement: arquitectura i psicologia. Per això, és d'esperar que el present treball marque un nou pas en aquesta direcció

La memòria doctoral es presenta en un format de compendi d'articles, estructurada en vuit capítols. El primer capítol introdueix i contextualitza el treball. El segon, detalla l'objectiu general i els objectius específics. El tercer, descriu la metodologia utilitzada, incloent-hi procediments, materials i eines. Els capítols quatre a sis presenten els articles d'investigació publicats que aborden cada objectiu específic. Cada article segueix un format estàndard amb introducció, metodologia, discussió i conclusions. El seté capítol analitza globalment els resultats i les seues limitacions. El vuité capítol ofereix la conclusió destacant la contribució significativa de la tesi.

# Abstract

*"We must not forget that architecture is built to live in, not just to look at".* With these words, architect Van Der Rohe emphasizes the importance of architectural design serving life and contributing to its improvement. This perspective highlights the significant connection between psychology and architecture, as the spaces we inhabit shape our personal development. Thus, each environment has a primary purpose and must be functional accordingly. Particularly, educational environments play a fundamental role in the teaching-learning process. Therefore, it is crucial to design these spaces not only to be pleasant for occupants but also to enhance the cognitive processes involved in education, ensuring a conducive environment for learning and personal growth. In line with this, the objective of this doctoral thesis is to analyze the relationship between three classroom design elements (light, color, and dimension) and three cognitive processes of students (memory, attention, and preference for the environment).

To address this, three laboratory studies were conducted. These studies involved the cognitive evaluation of each participant while immersed in virtual classrooms that differed only in the three design elements under study, thus replicating a real environment with controlled variations. For this purpose, two specific instruments compatible with each other and highly relevant to the field of architecture were used: 1) virtual reality as a tool for space visualization and 2) performance of specific attention, memory, and preference tasks as tools for measuring subject cognition. The first study analyzed the effect of design interventions (in

terms of light, color, and dimension) on students' attention and memory performance and their preference, examining the relative impact of each. This comparative approach allows understanding which physical changes in the classroom are most sensitive to different cognitive processes of students. The study was conducted collectively with both genders and also separately. In the second study, the specific values of each of the three design elements studied (light: illuminance and color temperature; color: hue and saturation; dimension: height and width) were identified to improve the memory of men and women, minimizing differences between genders. On the other hand, the third study proposes a joint analysis of the three design elements through multi-objective linear programming to identify specific combinations of light, color, and shape that maximize benefits in terms of memory, attention, and preference.

The results of the first study showed that among the possible classroom interventions, lighting (compared to interventions in color or dimension) is the design element that most affects students' cognition. Although the cognition of men and women differs in their sensitivity to design changes, attention is the most sensitive cognitive process. The second study determined that the memory of men and women responds differently to the set of parameters of the studied classroom design elements. In this regard, a lighting color temperature of 6500K, blue wall color (Munsell, 5B) with high saturation, and wider classrooms, especially 7.2m wide, can be considered as a design that favors students' memory without creating gender differences. However, the approach of the third study highlighted that these elements do not affect all cognitive processes uniformly and that there is also a synergistic influence between them. This underscores the importance of studying the environment-person relationship from a holistic perspective. Thus, the combined effect of 100lx, 6500K, 4.4m high, 8.4m wide, a 5B or purple (Munsell, 5P / 5PB) color of low saturation in the classroom optimizes students' memory, attention, and preference. Additionally, it was also concluded that the same combination of purple color with an illuminance of 300lx, a height of 3.2m or 4.4m, and a width of 6m or 8.4m, respectively, results in even higher levels of memory and attention.



From the set of results, it is concluded that the classroom elements are interconnected, thus needing to be studied as a whole. Added to this is the complexity of the student since their cognition does not follow a single pattern. Therefore, studying this paradigm as a whole is necessary. In this sense, a valuable methodology is explored, combining space control tools like virtual reality with cognitive measurement tools like validated specific tasks. The approach developed in this work could be promising as it represents the beginning of multidisciplinarity in which the two areas of knowledge—architecture and psychology—are combined. Therefore, it is expected that this work will mark a new step in that direction.

The doctoral thesis is presented in a compendium of articles format, structured in eight chapters. The first chapter introduces and contextualizes the work. The second details the general objective and three specific objectives of the thesis. The third describes the methodology used, including procedures, materials, and tools. Chapters four to six present the published research articles addressing each specific objective. Each article follows a standard format with introduction, methodology, discussion, and conclusions. The seventh chapter globally analyzes the results and their limitations. The eighth chapter offers the final conclusion highlighting the significant contribution of the thesis.

# Índice

# Capítulo 1.

## Introducción general

La controvertida relación entre la genética y el entorno ha sido objeto de estudio a lo largo del tiempo. Históricamente, las diferentes teorías pueden clasificarse en dos grandes perspectivas que han competido por la supremacía en este campo. Por un lado, el innatismo postula que los seres humanos están predeterminados genéticamente y que esta programación es inmutable; por otro lado, el ambientalismo defiende la noción de que todo individuo nace como una "tabula rasa", siendo el entorno el que determina su desarrollo (Thomas, 2001). Así, se puede considerar que la realidad probablemente se encuentra en un punto intermedio, donde tanto la genética como el entorno juegan roles cruciales y complementarios en el desarrollo humano.

Las corrientes contemporáneas buscan conciliar estas visiones aparentemente opuestas. La comprensión actual acepta que la predisposición innata grabada en nuestra genética condiciona la manera en que interactuamos con el entorno. Sin embargo, también nos revela que el entorno desempeña un papel crucial en la modificación de dicha genética a través de procesos epigenéticos (Day & Sweatt, 2011; Lacal & Ventura, 2018). La epigenética, un término acuñado inicialmente por Waddington (1940), se refiere a los cambios en la expresión genética que no implican alteraciones en la secuencia del ADN, sino que son influenciados por factores ambientales. Este concepto aborda la compleja interrelación entre naturaleza y entorno (Deans & Maggert, 2015) que se manifiesta de forma tangible en varios aspectos de nuestra vida (Taylor et al., 2016), incluido el diseño de los espacios que habitamos. En este sentido, el propio diseño de los espacios tiene capacidad para modelar las capacidades individuales, la expresión de nuestra identidad y, también, la salud como se demostró en el estudio pionero llevado a cabo por Ulrich (1984). Al aplicar esta comprensión al diseño de espacios, emerge la imperiosa necesidad de generar entornos que, no solo se ajusten a las necesidades perceptivas y estéticamente agradables, sino que también enriquezcan la dimensión cognitiva de los individuos.

El diseño de espacios centrado en la persona se posiciona como una respuesta directa a este desafío. Esto implica un estudio multidimensional del entorno que va más allá de la mera disposición física, abordando también la compleja interacción del individuo con su entorno (Rebernik et al., 2019). Es un reto complejo, ya que el individuo debe ser comprendido desde una visión holística. En este enfoque, el diseñador no solo considera las necesidades del usuario basándose en su propia interpretación, sino que además emplea métodos cuantificables para medir dichas necesidades y establecer métricas de la funcionalidad que se pretende alcanzar con el espacio. La finalidad es enriquecer la experiencia estética del usuario y, al mismo tiempo, contribuir a su desarrollo haciéndolo partícipe indirectamente del diseño (Eason, 1995).

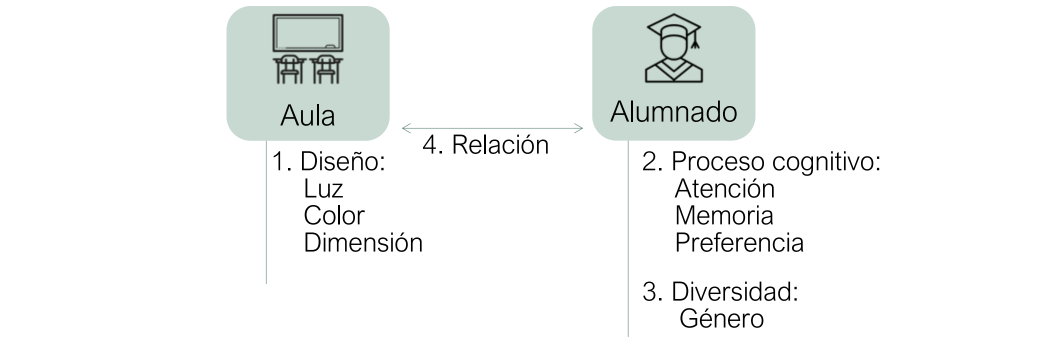
En este contexto, el presente capítulo se centra en esta relación humano-espacio, en el ámbito educativo. Para ello, se analizan varias variables clave: los elementos de diseño del aula, los procesos cognitivos del alumnado, la diversidad de las personas y la relación entre ellas (ver Figura 1). Cada uno de estos cuatro aspectos claves se detalla en los cuatro apartados siguientes.

## 1. El estudio del diseño del aula y su influencia en los procesos cognitivos del alumnado

Los espacios educativos han sido recurrentes en la literatura científica como uno de los contextos más influyentes en el humano (Cuban, 2018), proporcionando el marco físico para el desarrollo del conocimiento. Este especial interés en dichos espacios puede justificarse por el hecho de que pasamos una parte signifi-



Figura 1. Esquema gráfico de la relación Humano-Espacio en el ámbito educativo.




cativa de nuestra vida en ellos como estudiantes. Concretamente, el actual sistema educativo español (Ley Orgánica 3/2020, de 29 de diciembre) contempla diez años de escolarización obligatoria, ampliable con la educación infantil y/o superior.

En esta línea, el ambiente físico del aula influye en el rendimiento de los estudiantes. Se ha demostrado que esta influencia se da en varios niveles, tanto en la educación primaria (Hathaway, 1995; Tanner, 2000) y secundaria (Shamaki, 2015) como universitaria (Lizzio et al., 2002). Ello incluye la disposición del mobiliario (Baum, 2018; Earthman, 2002; Fisher, 2001; Park & Choi, 2014; Ramli et al., 2013; Wannarka & Ruhl, 2008), la presencia de elementos vegetales (Daly et al., 2010; Doxey et al., 2009; Van den Berg et al., 2017) y también aspectos simbólicos como carteles (Cheryan et al., 2014). Además, otra parte considerable de la investigación del entorno educativo se ha enfocado en aspectos estructurales y ambientales del aula, tales como la temperatura, la calidad del aire (Earthman, 2004; Choi et al., 2014; Schneider, 2002) y acústica (Crandell & Smaldino, 2000; Picard & Bradley, 2001). Estos elementos están más desarrollados debido a su estrecha relación con la eficiencia energética, llegando incluso a contemplarse algunos de ellos en la normativa. Sin embargo, otros elementos del diseño, como la luz, el color y la dimensión, también influyen significativamente en el proceso de aprendizaje, pero no han sido abordados con la misma profundidad o carecen de consenso a pesar de su uso frecuente en el diseño de aulas.

La luz, por ejemplo, ha sido objeto de numerosos estudios, aunque no siempre con resultados consensuados. De esta forma, se ha demostrado la relación directa de dos de sus componentes claves: la iluminancia y la temperatura de color (CCT), con la concentración de los estudiantes (Sleegers et al., 2013). La baja iluminancia se ha asociado con un rendimiento cognitivo inferior (Hathaway, 1995), mientras que una mayor iluminancia está vinculada a mejores resultados en pruebas de atención (Llinares et al., 2021c; Smolders & de Kort, 2014). No obstante, otros autores han determinado que un nivel de iluminancia bajo es mejor valorado y da lugar a un mejor rendimiento de comprensión lectora (Marchand et al., 2014), rendimiento cognitivo (Huiberts et al., 2015) y niveles de memoria (Llinares et al., 2021c). Asimismo, el análisis de la CCT tampoco arroja resultados concluyentes. De esta forma, la CCT influye en el procesamiento cognitivo, donde valores más altos pueden mejorar la concentración y el rendimiento en tareas específicas (Keis et al., 2014; Mills et al., 2007; Viola et al., 2008), incluyendo la atención y la memoria (Llinares et al., 2021c). Por su parte, otros estudios han concluido que la CCT no tiene influencia en procesos cognitivos como la atención (Smolders & De Kort, 2017). A pesar de estas discrepancias, sí parece haber un consenso en cuanto a los efectos positivos de la presencia de luz natural (Heschong et al., 2002; Tanner, 2009).

Por otro lado, el color del aula también juega un papel significativo en la experiencia educativa. La mayoría de investigaciones han hecho la aproximación del color en cuanto a las paredes del aula. Estudios previos han revelado que los espacios cromáticos, frente a los blancos o acromáticos, favorecen una mayor eficiencia en tareas cognitivas complejas (Cockerill & Miller, 1983; Kwallek et al., 1996; Xia et al., 2016). Se ha observado que los tonos fríos (Llinares et al., 2021a), como el verde (Bernardo et al., 2021), mejoran la atención y la memoria de los estudiantes. Por su parte, otros autores matizan que esta afirmación depende de la naturaleza y dificultad de la tarea (Barrett et al., 2013; Mahnke, 1996). Otra variable del color que hay que tener en cuenta es la saturación, aunque esta no ha sido abordada específicamente desde el ámbito educativo (Cubukcu & Kahraman, 2008; Gao & Xin, 2006). Estos hallazgos subrayan la importancia de profundizar sobre el color del entorno educativo.



Además, las dimensiones físicas del aula, como la altura del techo y el espacio disponible, también influyen en el rendimiento y la interacción de los estudiantes. Los techos más bajos, por ejemplo, promueven la cooperación del alumnado en entornos escolares (Read et al., 1999). Otros estudios también han abordado la influencia de la altura del techo, aunque no se han centrado específicamente en el ámbito educativo (Earthman, 2004) o bien se han centrado en el ámbito educativo pero desde la perspectiva del profesorado (Ahrentzen & Evans, 1984). Por su parte, la planta del aula es otro componente dimensional abordado. En este sentido, las aulas en forma de “L” han sido descritas como facilitadoras del agrupamiento entre los estudiantes para realizar actividades y mejorar el aprendizaje (Lippman, 2004). También se ha observado que las aulas más pequeñas se relacionan con un mejor rendimiento y una mayor excitación emocional entre los estudiantes (Llinares et al., 2021b). En cualquier caso, este es el aspecto menos concluyente debido a su escasa exploración en la literatura científica. Por ello, se debe considerar cuidadosamente la influencia de la dimensión del aula en el proceso de aprendizaje del alumnado.

Con todo ello, los estudios sobre el impacto de la luz, el color y la dimensión en el entorno educativo han arrojado resultados variados y a veces contradictorios. Esto indica que no existe un consenso claro sobre cómo estos elementos de diseño afectan de manera uniforme al rendimiento y la experiencia de los estudiantes. Esta diversidad de hallazgos sugiere que aún se necesita una mayor profundización y exploración en esta área para comprender mejor las interacciones complejas entre el diseño del aula y el aprendizaje estudiantil.

## 2. Los procesos cognitivos del alumnado en el aula

La clasificación de los procesos cognitivos es una tarea compleja debido a la naturaleza abstracta y multifacética de la mente humana. Los procesos cognitivos son constructos teóricos que representan diversas funciones mentales involucradas en el procesamiento de la información y la conducta. A lo largo de la historia, se han realizado varios intentos para categorizar y organizar estos procesos (Gain, 2018; Hay et al., 2017; Metzler & Shea, 2011). Sin embargo, las definiciones y los límites entre ellos suelen ser difusos y objeto de debate. Esta dificultad también se debe a que los términos "procesos cognitivos", "capacidad cognitiva" y "funciones cognitivas" se usan de forma indiscriminada, lo que contribuye a la confusión y a la falta de consenso en su clasificación.

Algunas clasificaciones consideran que la percepción, la atención y la memoria son procesos cognitivos básicos (Zhang, 2019). Estos procesos sustentan y dan forma a otros procesos cognitivos más complejos o funciones ejecutivas superiores, como el lenguaje, la planificación, la resolución de problemas y la toma de decisiones. Así, por ejemplo, el lenguaje requiere procesos perceptivos para interpretar sonidos y símbolos, atención para enfocarse en la comunicación verbal, y memoria para almacenar y recuperar vocabulario y reglas gramaticales. Sin embargo, la delimitación exacta de estos procesos y sus interrelaciones sigue siendo un desafío. Por ejemplo, el papel exacto de la atención en el procesamiento del lenguaje puede variar según el grado de familiaridad con el contexto. De acuerdo a ello, algunos modelos contemporáneos proponen una visión más integradora de los procesos cognitivos, donde múltiples funciones interactúan dinámicamente para dar lugar a la cognición humana compleja. Esta visión se ve respaldada por investigaciones neurofisiológicas que, empleando técnicas anatómicas (Toga et al, 1994) y de neuroimagen funcional o estructural (D'esposito et al., 1995; Tamraz et al., 2004), revelan numerosas conexiones de aferencias y eferencias entre diversas estructuras cerebrales. Por ejemplo, el hipocampo es considerado una estructura cerebral fundamental para la consolidación de la memoria y la orientación espacial. Sin embargo, este no se encuentra aislado en el encéfalo, sino que muestra conexiones neuronales con el córtex prefrontal (D'esposito et al., 1995) u otras áreas corticales (Cenquizca & Swanson, 2007), asociadas a diferentes procesos cognitivos como la memoria de trabajo y la percepción, respectivamente. En cualquier caso, la clasificación jerárquica de los procesos cognitivos facilita la aproximación al estudio de estos procesos, permitiendo una organización estructurada y sistemática.



De acuerdo a la clasificación propuesta por Zhang (2019), la percepción, como uno de los procesos cognitivos básicos, es la habilidad de organizar y asimilar la información sensorial que nos rodea. Dado que recibimos constantemente inputs sensoriales del entorno, la percepción es una función cognitiva que se encuentra en uso continuo. Implica la capacidad de percibir e interpretar los diferentes elementos externos. Debido a este componente subjetivo y esta naturaleza interpretativa, es difícil consensuar una métrica de medición de la percepción del espacio. Por ello, se suele relacionar la percepción con la preferencia por el espacio. En este sentido, es coherente pensar que las aulas deben ser ambientes donde los estudiantes se sientan cómodos y a gusto. La importancia de esta preferencia por el espacio como medición del proceso cognitivo perceptivo está justificada por su posible contribución al bienestar emocional de los estudiantes (Gao et al., 2019; Loewen & Suedfeld, 1992), lo cual, a su vez, favorece su disposición para el aprendizaje (Aldridge & Rowley, 1998; Bryan et al., 1996). Estudios previos han mostrado una relación positiva entre las preferencias de los individuos por su entorno y su rendimiento (Cockerill & Miller, 1983; Shen et al., 2020), influenciado por un estado de ánimo tranquilo (Costa et al., 2018). Sin embargo, otras investigaciones sugieren que el estado de ánimo no necesariamente se ve afectado por la preferencia del entorno (Lipson-Smith et al., 2021).

La falta de consenso subraya que el diseño del aula no se limita solo a la percepción, sino que desempeña un papel crítico en el proceso de aprendizaje. Este proceso implica la adquisición, procesamiento y almacenamiento de información para su uso futuro. En este contexto, la memoria juega un papel crucial (Aparicio & Rodriguez, 2015) ya que implica la retención y recuperación de información. El modelo clásico de la memoria propuesto por Atkinson y Shiffrin (1968) describe este proceso como un sistema compuesto por un registro sensorial, una memoria a corto plazo y una memoria a largo plazo. Posteriormente, Baddeley y Hitch (1974) desarrollaron un modelo funcional al que llamaron memoria de trabajo. Este modelo está compuesto por tres componentes principales: la agenda visoespacial, que maneja la información visual y espacial; el buffer episódico, que integra información de diferentes fuentes en una única representación coherente; y el bucle fonológico, que se encarga de procesar y almacenar información auditiva y verbal. Todos estos componentes son controlados por el ejecutivo central, que dirige la atención y coordina las actividades de los otros componentes. De esta forma, tanto el registro sensorial, del modelo clásico, como el ejecutivo central, del modelo funcional, están influidos por la atención (Awh et al., 2006). De esta forma, la atención facilita la concentración en diferentes tareas y la absorción efectiva de la información, es decir, se refiere a la capacidad de seleccionar y concentrarse en estímulos específicos. Ello destaca la atención y la memoria como principales funciones implicadas en la capacidad de aprendizaje (Bernabéu, 2017). En este sentido, un diseño centrado en el estudiante debe tener en cuenta la gestión de la atención y la memoria para optimizar el aprendizaje. Esto implica generar ambientes que mantengan y dirijan la atención de los estudiantes, minimizando las distracciones innecesarias y proporcionando estímulos que fomenten la concentración y el almacenamiento de la información.

Por consiguiente, es necesario contemplar información del usuario en el diseño de espacios educativos centrados en la persona. Esto incluye no solo el aspecto perceptivo cuantificado a partir de la preferencia del espacio, sino también datos específicos sobre la memoria y la atención. Al integrar estas consideraciones, se pueden generar entornos que sean funcionales y estéticamente agradables, pero también que favorezcan el rendimiento de los estudiantes.

## 3. La diversidad del alumnado en el aula

Es fundamental reconocer que la percepción y el aprendizaje de los alumnos son procesos cognitivos complejos influenciados no solo por el entorno físico en el que tienen lugar, sino también por otros factores. Algunos de estos factores son externos, como las interacciones estudiante-instructor (Lindblom-Ylänne et al., 2003), las condiciones socioculturales del entorno (Eccles, 2005), la participación de las familias en el aula (Gutiérrez-Fresneda, 2019) y el uso de metodologías específicas (Van Alten et al., 2019). Además, existen factores internos propios del alumnado (Beltrán-Velasco et al., 2021; Helal et al., 2018) que también ejercen influencia, como la cultura, el lenguaje, los estados emocionales (Hascher, 2010), la edad y las necesidades educativas individuales (Szumski et al., 2017). Estos factores internos son transversales a todos los estudios en este ámbito debido a su carácter intrínseco a cada usuario del espacio educativo.



El género es uno de los factores internos más investigado debido a su asociación con diferencias en la neurobiología cerebral, como han demostrado varios estudios (Andreano & Cahill, 2009; Grön et al., 2000; Persson et al., 2013). Estas diferencias tienen una importancia fundamental en la comprensión de las necesidades de aprendizaje de los estudiantes y en el procesamiento perceptivo del entorno educativo. En este sentido, estudios tradicionales centrados en los dos sexos genéticos (hombre y mujer), han evidenciado la existencia de diferencias en procesos específicos como la memoria de trabajo (Knez, 2001) y la atención selectiva (Merritt et al., 2007), las cuales pueden variar según la naturaleza del contenido de la tarea (Kaushanskaya et al., 2013). Estos hallazgos subrayan la importancia de considerar las diferencias de sexo en el aprendizaje.

Sin embargo, el sexo es una variable crucial no solo por estar implicada en los procesos cognitivos estrechamente relacionados con el aprendizaje sino porque también influye en procesos cognitivos implicados en la experiencia que tenemos del entorno. En este sentido, la percepción y la interacción con el entorno son notablemente distintas entre hombres y mujeres. Esta diversidad se evidencia en las estrategias utilizadas para la orientación y el desplazamiento espacial, según lo han destacado diversos investigadores (Fernández-Baizán et al., 2019; Persson et al., 2013; Tascón et al., 2017). Asimismo, la investigación en este campo ha revelado que ambos géneros procesan de forma diferente la información, incluyendo los elementos de diseño interior (Cheryan et al., 2011; Picucci et al., 2011). En términos generales, las preferencias por el color varían significativamente entre hombres y mujeres (Fortmann-Roe, 2013), y la iluminación puede afectar de manera diferencial la memoria en cada grupo (Yang & Jeon, 2020). Por tanto, estas variaciones resaltan la importancia de considerar el sexo como variable al diseñar entornos educativos y otros espacios compartidos, para asegurar que sean inclusivos y eficaces para todas las personas.

El diseño de espacios educativos inclusivos implica reconocer que diversos factores impactan de manera única en el proceso de aprendizaje y la interacción de cada estudiante con su entorno. Para construir entornos verdaderamente inclusivos que fomenten el éxito de todos los estudiantes, es esencial considerar el género como una variable clave en el diseño de estos espacios. Esto significa recopilar información de manera equitativa tanto de hombres como de mujeres para desarrollar un enfoque que sea sensible a las necesidades y preferencias de ambos grupos (Langdon et al., 2014). Al tener en cuenta las diferencias de género, entre otras diversidades, se favorece la creación de entornos educativos más efectivos y acogedores, que maximicen el potencial de todos los estudiantes

## 4. El estudio de la relación estudiante-aula

La relación entre el estudiante y el entorno educativo ha sido principalmente explorada desde la perspectiva de la psicología ambiental, que considera el entorno en un sentido más amplio (Russell & Ward, 1982). Esto implica que los análisis examinan la influencia de las características del entorno de manera general, sin estar específicamente vinculados a ningún elemento de diseño ni espacio particular (Martinovic et al., 2018). Sin embargo, estos estudios han contemplado diversos aspectos cognitivos del usuario, demostrando que elementos como el color (Al-Ayash et al., 2016) y la iluminación (Llinares et al., 2021c; Smolders et al., 2012) no generan una misma tendencia en las preferencias de los usuarios por los espacios, ni en su atención y/o memoria. Estas investigaciones resaltan la importancia de considerar la complejidad de la interacción entre los estudiantes y los entornos educativos, así como la necesidad de abordar estos factores de manera específica y contextualizada para optimizar el diseño de espacios que favorezcan el aprendizaje y el bienestar de todos los usuarios.

No obstante, la investigación está cada vez más enfocada en elementos específicos del diseño desde una perspectiva técnica (Marchand et al., 2014; Nyrud et al., 2014). A pesar de la variedad de características presentes en las aulas, estos estudios tienden a abordar elementos particulares del diseño de manera conjunta pero fragmentada, sin considerar plenamente su interacción. Las aulas exhiben múltiples atributos y es probable que los resultados derivados de análisis individualizados difieran de aquellos que surgen al considerar combinaciones de características. Por ejemplo, un adecuado nivel de iluminancia puede ser menos eficaz cuando se combina con un color o altura específica de techo, alterando así la percepción global del entorno por parte de los individuos.



Esta falta de consideración hacia las interacciones entre diversas características del diseño espacial subraya el axioma principal de psicología de la Gestalt: El todo es más que la suma de sus partes. Según esta corriente psicológica moderna, tendemos a percibir los elementos individuales como parte de un todo o una totalidad integrada, en lugar de verlos como entidades aisladas (Koffka, 1922). Los principios de organización perceptual de la Gestalt, tratan de describir nuestra forma de percibir el entorno, sugieren que el diseño espacial no solo afecta a cada elemento por separado, sino que influye en la experiencia perceptual global de un entorno, destacando así la importancia de considerar las relaciones entre los componentes del diseño para una percepción integrada y coherente del espacio.

En todos los casos, es notable que cada uno de los elementos se analiza de manera individual, lo que conduce a resultados menos concluyentes al no considerar el conjunto integrado de elementos que contribuyen a las características del espacio. Debido a esta aproximación fragmentada, es difícil encontrar estudios que apliquen una visión holística que contemple tanto la complejidad del espacio como las características y necesidades del usuario. Por consiguiente, es fundamental llevar a cabo investigaciones que examinen cómo diversos elementos de diseño pueden influir en la cognición del individuo, sin ignorar el posible impacto de sus interacciones mutuas, resaltando así la necesidad de estudios integrales que aborden la complejidad y las interrelaciones entre los elementos del diseño espacial para comprender mejor su efecto en la experiencia humana.

# Capítulo 2.

## Objetivos

El objetivo general de la tesis doctoral es analizar el efecto que tres elementos del diseño del aula (luz, color y dimensión) tienen en las funciones cognitivas del alumnado (atención, memoria y preferencia). Este objetivo general se desagrega en tres objetivos específicos. Cada uno de ellos se abordan de forma independiente en los tres capítulos siguientes y han sido desarrollado a partir de una motivación específica.

1. Analizar la magnitud del efecto de las intervenciones de diseño (en cuanto luz, color y dimensión) en el rendimiento de atención y memoria del alumnado y su preferencia hacia el entorno, analizando el impacto relativo de cada una de ellas en hombres y mujeres.

   Motivación: El estudio del efecto de los cambios en la luz, el color y la dimensión del aula (en referencia a un aula de control) favorece la concreción de estrategias de diseño. Ello permitirá establecer, de entre todas las intervenciones posibles a realizar, un orden de prioridad en función del propósito deseado para mejorar la experiencia educativa de los estudiantes. Este enfoque comparado permite comprender a qué cambios físicos del aula son más sensibles los diferentes procesos cognitivos del alumnado, pudiendo beneficiar o afectar negativamente a su rendimiento y su bienestar en el entorno escolar

2. Identificar los elementos de diseño del aula (luz, color y dimensión que consiguen mejorar la memoria de hombres y mujeres, minimizando las diferencias entre ambos géneros.

   Motivación: Profundizar en el estudio de la relación espacio-ser humano la perspectiva de género permite identificar cómo diferentes elementos de diseño afectan positiva o negativamente al rendimiento de memoria en estudiantes masculinos y femeninos. Esta consideración detallada no solo nos ayudará a comprender las diferencias en las experiencias y percepciones de ambos géneros dentro del entorno educativo, sino que también ofrecerá la oportunidad de diseñar aulas que favorezcan el aprendizaje y el bienestar de todos los estudiantes, independientemente de su género. Este enfoque podría proporcionar valiosas pautas para generar entornos educativos más inclusivos y efectivos, promoviendo así un ambiente de aprendizaje enriquecedor para todos.

3. Optimizar el conjunto de procesos cognitivos significativos en el aprendizaje (memoria, atención y preferencia) mediante configuraciones específicas de luz, color y dimensión en el aula.

   Motivación: Una aproximación sistemática y global al aula y a los estudiantes posibilita la determinar el mejor diseño posible del entorno educativo en beneficio del conjunto del alumnado. La aplicación de la programación lineal multiobjetivo permite optimizar múltiples aspectos cognitivos de manera simultánea y considerar posibles compensaciones entre ellos pese a verse afectados por el entorno de diferente forma. En este contexto, se busca identificar las combinaciones de parámetros de diseño que maximicen los beneficios en términos de memoria, atención y preferencia, reconociendo que ciertas configuraciones pueden favorecer aspectos particulares. Este enfoque proporciona un marco riguroso para diseñar aulas que favorezcan un ambiente propicio para el aprendizaje, teniendo en cuenta las complejas interacciones entre los diferentes elementos de diseño y procesos cognitivos involucrados.

# Capítulo 3.

## Metodología general

Con el fin de desarrollar las correspondientes investigaciones que abordan los objetivos planteados en el capítulo anterior, se llevaron a cabo diferentes estudios de experimentación realizados en laboratorio. Dichas experiencias implican la recogida de información psicológica de una muestra de sujetos mientras visualizan, de forma individual, diferentes configuraciones de un aula en un entorno virtual. El uso combinado de ambos tipos de instrumentos en esta metodología enriquece el estudio más tradicional del diseño arquitectónico.

En las últimas décadas ha habido avances significativos en las simulaciones ambientales utilizadas en estudios arquitectónicos y ambientales para representar escenarios a evaluar, tanto a nivel de formatos como de soportes de presentación. Históricamente, las herramientas empleadas para evaluar el diseño espacial se basaban en métodos estáticos y no inmersivos, como fotografías del espacio o representaciones visuales (Stamps, 1990,1993). No obstante, estos formatos presentan limitaciones, especialmente en cuanto al control de variables y los costos asociados con la modificación de entornos reales. Además, al ser formatos de naturaleza estática no ofrecen una experiencia comparable a la arquitectónica: que es un continuo experiencial multisensorial. La Realidad Virtual (en adelante RV) permite modificar diseños espaciales de manera eficiente, minimizando los costos y manteniendo constantes otras variables de diseño. También proporciona una experiencia inmersiva que hace que el individuo se sienta realmente presente dentro del espacio simulado (Barranco et al., 2023), es decir, que tenga la sensación de "estar allí" (Lehman & Conceição, 2010). Numerosos estudios respaldan la validez de esta tecnología, argumentando que el comportamiento de las personas en entornos virtuales replica de manera similar su conducta en entornos reales (Armougum et al., 2019; Higuera-Trujillo et al., 2017; Llinares et al., 2023; Marín-Morales et al., 2019). La convergencia de la tecnología de RV con el análisis del diseño ambiental ofrece una oportunidad única para investigar y comprender las interacciones complejas entre el entorno físico y el humano.

De igual forma, en la mayoría de estudios del ámbito de la arquitectura, la participación de los sujetos se limita a responder preguntas sobre su valoración personal de distintos entornos (Nyrud et al., 2014; Stamps, 1990, 1993). La preferencia declarada por un sujeto hacia un espacio es, sin duda, una métrica que ofrece información valiosa sobre sus percepciones de dicho espacio (Baird et al., 1978), pero estos datos deben complementarse con otras métricas objetivas. En este sentido, la aproximación de la memoria y atención (procesos directamente relacionados con el aprendizaje) se ha hecho a través de tareas específicas del ámbito de la psicología que puede aplicarse con éxito al estudio del entorno (Cockerill & Miller, 1983; Shen et al., 2020). En cualquier caso, el efecto del diseño en los diferentes procesos cognitivos no siempre coincide (Llinares et al., 2021c; Al-Ayash et al., 2016), por lo que es esencial recopilar una variedad de medidas sobre la persona de modo que proporcione una comprensión más completa de la interacción entre estudiante-aula.

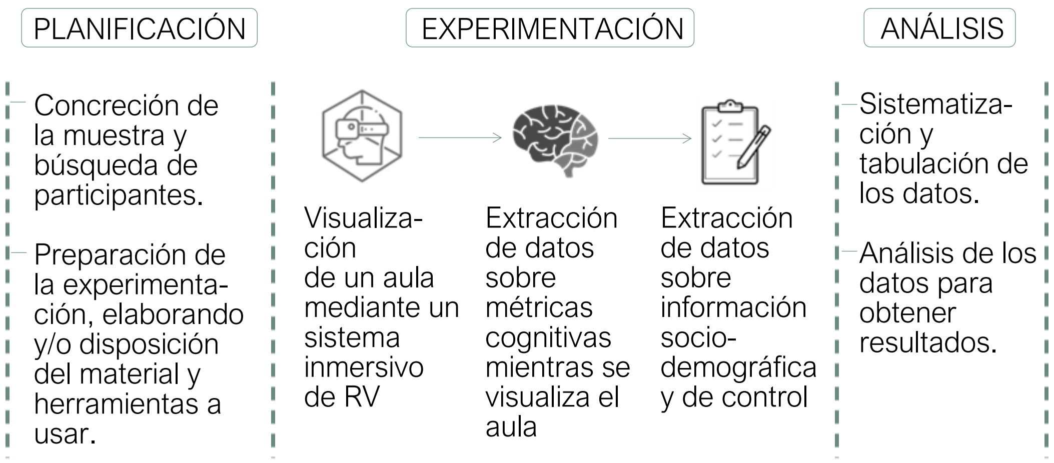
Aunque cada uno de los estudios presentados en la memoria doctoral tienen unas características específicas, existe una metodología de experimentación común (Figura 2). Esta metodología presenta tres fases consecutivas claramente diferenciadas: (1) preparación de la experimentación, (2) desarrollo de la experimentación y (3) análisis de datos.

## 1. Preparación de la experimentación

Esta fase se refiere al conjunto de actividades realizadas previamente a la experimentación. Ello implica el acondicionamiento de la sala experimental, la or-



Figura 2. Secuencia general de las fases que contempla la metodología empleada.




ganización y citación de los participantes. Todo ello, después de haber concretado las características de la muestra de sujetos, la sistematización y elaboración de los estímulos virtuales presentados, así como la concreción y obtención de los materiales y herramientas necesarias para la medición del participante.

### *1.1. Muestra.*

Los tres estudios se llevaron a cabo con diferentes muestras de participantes. Todas ellas estaban balanceadas en cuanto al género, con niveles equitativos de hombres y mujeres. Los criterios de inclusión fueron tres: (1) pertenecer a una población estudiantil universitaria recibiendo algún tipo de formación en el momento de ejecución del estudio, (2) tener una correcta agudeza visual con la mayor corrección óptica posible y (3) poseer nacionalidad española. El primer criterio asegura que los participantes estén activamente involucrados en un proceso de formación. De esta forma, se busca mantener una relación directa con el contexto educativo que se está investigando, lo cual es crucial para comprender cómo ciertos factores pueden afectar a los estudiantes en su entorno académico. Con el segundo criterio se minimizan las posibles influencias de las deficiencias visuales en la percepción del entorno. Además, esto es importante debido a la incompatibilidad del uso de lentes correctivas con los soportes de realidad virtual. Por último, el tercer criterio se implementa considerando que las aulas educativas y los contextos de aprendizaje pueden variar significativamente entre diferentes países. Asimismo, este último criterio asegura un nivel adecuado de español, idioma en el que se desarrolló la experimentación. La Figura 3 muestra a un participante durante la experimentación utilizando los tres principales dispositivos empleados para presentar y visualizar el estímulo, así como para recoger información del sujeto.

### *1.2. Estímulos.*

Todos los estímulos consistieron en aulas universitarias de realidad virtual. El estímulo llamado “aula base” era una réplica virtual de un aula real tipo de la Universidad Politécnica de Valencia (Figura 4), seleccionada por ser un aula universitaria representativa. El resto de estímulos también partían de este aula real diferían, entre sí y con respecto a dicha aula base, en modificaciones de valores de cada uno de los parámetros de los elementos de diseño estudiados. Los valores de modificación seleccionados se basaron en criterios estándar de construcción (Tabla 1). Para la iluminación, se seleccionaron los valores de iluminación y CCT de las luminarias más comunes en el mercado. En cuanto al color, se optó por 10 tonalidades diferentes distribuidas de manera uniforme en el círculo cromático de Munsell, con dos saturaciones siempre separadas por 6 unidades de croma (dando lugar a una saturación alta y baja) y un valor constante intermedio de 5 unidades. En cuanto a la geometría, el criterio utilizado fue emplear varias medidas de ancho y alto determinadas al sumar o restar la dimensión de los módulos/unidades frecuentemente empleados en la fabricación de suelos y techos falsos.



Figura 3. Participante durante la sesión experimental.

Figura 4. Replica virtual del aula base con las siguientes características físicas: color de pared blanco neutro (N5 en el sistema de color Munsell), altura, ancho y largo representativos de las aulas de la universidad (3,80 m × 8,40 m × 16,50 m) e iluminación artificial convencional (iluminancia 300lx, CCT 4000K, y flujo directo).

Tabla 1. Características del aula estudiadas. Nótese que iluminancia y CCT se refieren a la luz interna artificial del aula, alto del techo y ancho de planta constituyen la dimensión, mientras que saturación y tono aluden al color de las paredes.

| Elementos | ILUMINACIÓN | | DIMENSIÓN | | COLOR | |
|---|---|---|---|---|---|---|
| Parámetros | Iluminancia | CCT | Alto | Ancho | Saturación | Tono |
| Valores | 500lx<br>300lx<br>500lx | 10500K<br>6500K<br>4000K<br>3000K | 4.4 m<br>3.8 m<br>3.2 m<br>2.6 m | 8.4 m<br>7.2 m<br>6 m<br>4.8 m<br>3.6 m<br>2.4 m | Baja<br>Alta | 5P<br>5R<br>5Y<br>5G<br>5B<br>5GY<br>5YR<br>5RP<br>5PB<br>5GB |

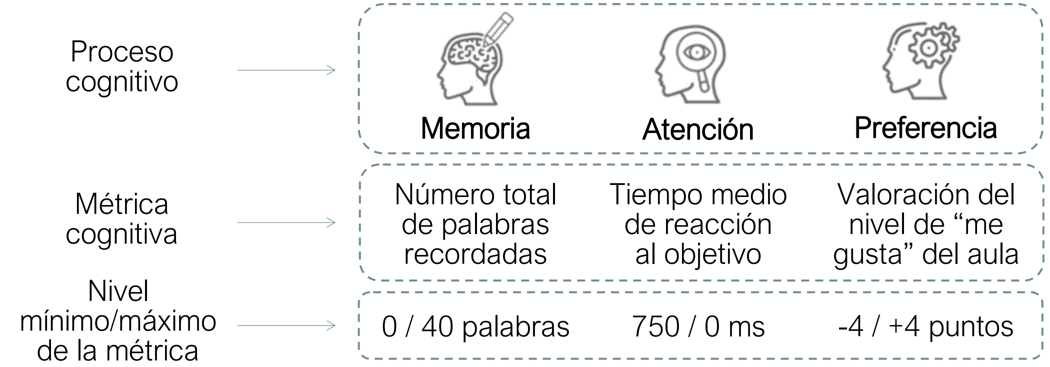


Las aulas virtuales fueron desarrolladas mediante un proceso de modelado y renderizado mediante el uso de Rhinoceros (v.5.0) y V-Ray Renderer (v.3.3) o Corona Renderer (v.2.0), respectivamente, funcionando estos dos últimos software en Autodesk 3ds Max (v.2014). Los renders se configuraron como panoramas de 360°, guardados en formato JPG con una resolución de 8000 × 4000 píxeles. Todos los participantes experimentaron la inmersión en las aulas desde el mismo punto en el reder: sentado en posición central de la segunda fila de mesas (ver Figura 4). Las imágenes fueron implementadas en Unity3D (v5.6), un programa instalado en un ordenador de mesa. El participante visualizaba el estímulo a través del dispositivo HTC Vive (resolución:1080×1200 píxeles por ojo; campo de visión: 110º y tasa de refresco: 90Hz), al mismo tiempo que un ordenador portátil controlaba la recogida de datos (ver Figura 3).

### *1.3. Herramientas de medición.*

Se recopilaron diversos datos de cada sujeto: métricas cognitivas de preferencia, atención y memoria (Figura 5), así como información sobre la sensación de presencia generada por la RV y sociodemográfica. Las herramientas utilizadas para obtener esta información del sujeto se describen a continuación.

Figura 5. Esquema resumen del conjunto de métricas cognitivas recogidas.



Atención. El rendimiento de la atención se midió a partir de una tarea psicológica que requería reacciones rápidas a ciertos estímulos auditivos. Durante esta prueba, los participantes escucharon una serie de 40 sonidos, entre los cuales había 4 tipos diferentes. Se les indicó que debían responder haciendo clic únicamente cuando escucharan un sonido específico (el estímulo objetivo), ignorando los otros sonidos (distractores). Los participantes tenían un límite de tiempo de 750 milisegundos después de la presentación de cada sonido para realizar el clic en caso de escuchar el estímulo objetivo. Esta tarea se repitió tres veces, con un total de 120 sonidos escuchados por cada participante, de los cuales 24 eran estímulos objetivo y 96 eran distractores. La presentación y aleatorización de los sonidos fue desarrollada y programada específicamente para este experimento. La métrica de atención sostenida se basó en los tiempos de reacción promedio a los estímulos objetivos. Un tiempo de reacción más corto indicaba un mejor desempeño en la prueba. Esta tarea es similar a las realizadas en las pruebas de rendimiento auditivo continuo (Seidman et al., 1998).

Memoria. El rendimiento de la memoria se evaluó mediante una tarea psicológica en la que los participantes debían memorizar una lista de palabras transmitidas por un dispositivo de grabación. Siguiendo el enfoque de Alonso et al. (2004), se les presentó una lista de 15 palabras pertenecientes al mismo campo semántico, seleccionadas aleatoriamente de un conjunto total de 16 listas. Estas palabras fueron presentadas a intervalos de 15 segundos. Inmediatamente después de la presentación de cada lista, los participantes disponían de 30 segundos para verbalizar todas las palabras recordadas. Esta tarea se repitió tres veces, escuchando un total de 45 palabras que fueron presentadas utilizando el sistema Loquendo TTS 7 y reproducidas a través de Windows Media Player. La métrica de memoria de trabajo se basó en el número total de palabras correctas recordadas. Por lo tanto, cuanto mayor fuera el número de palabras recordadas, mejor sería el resultado. Esta tarea es similar al paradigma DRM (Beato & Díez, 2001).

Preferencia. La aproximación de la percepción se llevó a cabo a través de los niveles de preferencia. Para evaluar las preferencias del entorno, se diseñó una pregunta específica para el estudio. Consistió en una pregunta de autoinforme dirigida a los participantes sobre sus percepciones del entorno que estaban experimentando. A los sujetos se les solicitó responder utilizando una escala Likert que iba de -4 a 4, la cual se presentó en el aula virtual que se estaba visualizando en ese momento. Se les pidió que evaluaran en qué medida estaban de acuerdo con la siguiente afirmación: "En general, me gusta esta clase". Una puntuación de -4 indicaba un completo desacuerdo con la afirmación, mientras que +4 indicaba un total acuerdo. De este modo, se evaluaron sus preferencias personales y su nivel de satisfacción con el entorno del aula, proporcionando así una métrica de preferencia ambiental. Esta pregunta se basó en una metodología similar utilizada por Galindo y Corraliza (2012) para evaluar juicios de preferencia general en la población española. Las respuestas de los participantes fueron proporcionadas oralmente a los entrevistadores, quienes las registraron para obtener la métrica de preferencia

Nivel de presencia. Para cuantificar el nivel de sensación de presencia de los sujetos en entornos virtuales, se implementó un cuestionario SUS (Slater, et al., 1994). Este cuestionario utiliza una escala Likert de 6 puntos (1-7) y es ampliamente utilizado para medir y comprender la sensación de presencia en entornos de realidad virtual. Las puntuaciones bajas, más cercanas a 1 en la escala, indican que los sujetos perciben los entornos como artificiales, mientras que puntuaciones altas, más cercanas al máximo de 42 (es decir, 7 puntos multiplicados por 6 ítems), reflejan una alta sensación de presencia en el entorno virtual. Basándose en investigaciones previas, se estimó que las puntuaciones de 24 o más representaban una sensación óptima de presencia en el entorno virtual (Slater & Steed, 2000).

Datos sociodemográficos. Se administró un cuestionario sociodemográfico que incluía preguntas sobre diversas variables. Estas preguntas abordaban aspectos como la edad, el género, características visuales relevantes (como la agudeza visual o el uso de lentes correctivos), nivel educativo, y otras variables pertinentes para el estudio. La inclusión de este cuestionario permitió obtener un perfil más completo de los participantes y considerar cómo estas variables podrían influir en sus respuestas y experiencias en los entornos de simulación virtual.

## 2. Desarrollo de la experimentación

La experimentación en laboratorio se llevó a cabo siguiendo un protocolo específico. Su uso en el laboratorio aumenta el control de variables externas, asegurando así que cualquier cambio observado sea atribuible únicamente a las condiciones evaluadas. De esta forma, ceñirse al protocolo minimiza las posibles influencias del sesgo del experimentador (Ellsworth, 1978), garantizando la objetividad y la reproducibilidad de los resultados obtenidos. El protocolo en cuestión se diseñó con diferentes actividades agrupadas en tres fases consecutivas: pre-experimental, experimental y post-experimental (Tabla 2).

En la primera fase, pre-experimental, se llevó a cabo la bienvenida del participante, proporcionando instrucciones básicas sobre el estudio y obteniendo su consentimiento informado mediante la firma del documento correspondiente. También se aplicó la prueba dicotómica D-15 de Farnsworth-Munsel de apreciación del color, seguido por la colocación con precisión de los dispositivos necesarios para la visualización virtual. Estas actividades son fundamentales para establecer una comunicación clara, garantizar la comprensión, preparar los equipos esenciales y evaluar la capacidad visual necesaria para el estudio. Posteriormente, se llevó a cabo una segunda actividad que implicó la visualización de un escenario virtual de prueba. Ello permite la familiarización del participante con las condiciones del estudio. Así se persigue reducir el efecto sorpresa de aquellos participantes novatos que usan la RV por primera vez (Miguel-Alonso et al., 2023), facilitar su adaptación al entorno experimental, reducir la ansiedad y garantizar mediciones precisas. El entorno simulado usado para esta habituación se diferencia físicamente de las aulas de estímulo del experimento, con un diseño sencillo, colores e iluminación neutros y sin elementos identificativos.

La segunda fase comenzó con las instrucciones generales, en las que se indicaba al sujeto el inicio de la fase experiencial del aula. Luego se reprodujo automáticamente el audio de preparación. Este es un audio de relajación que tiene la finalidad de reducir la fatiga a la presentación de escenarios virtuales (Lee et al., 2021). Inmediatamente después de reproducir el audio, se proyectó en el dis-



Tabla 2. Secuencia general de la experimentación.

| Fase | | Actividades |
|---|---|---|
| PRE | | INICIO: Preparación del participante. |
| PRE | | ESCENARIO DE PRUEBA: Visualización de escenario inicial. *"A continuación, entrarás en una sala. Tómate tu tiempo para familiarizarte con este escenario virtual de prueba y asegurarte de estar cómodo y preparado antes de comenzar el estudio principal".* |
| EXPERIENCIAL | | INSTRUCCIONES: Indicaciones generales. *"A continuación, escucharás un audio seguido de una visualización en un espacio. Imagina que este espacio es el aula universitaria donde recibes clases. Observa el entorno durante 90 segundos. Después, llevarás a cabo una serie de tareas y cuestionarios. Recuerda que en los cuestionarios no hay respuestas correctas ni incorrectas."* |
| EXPERIENCIAL | | AUDIO: Escucha de audio inicial de preparación |
| EXPERIENCIAL | EXPERIENCIA DEL AULA | TAREA DE MEMORIA. *"A continuación escucharás una lista de palabras. Intenta recordarlas. Después se te pedirá que las repitas sin importar su orden en un tiempo de 30 segundos. Esto se repetirá tres veces".* |
| EXPERIENCIAL | EXPERIENCIA DEL AULA | TAREA DE ATENCIÓN. *"A continuación escucharás una serie sonidos. Debes reaccionar lo antes posible ante un estímulo concreto haciendo un solo clic de ratón, y evitar hacerlo ante otros. El estímulo al que debes reaccionar es este [sonido#1]; y los estímulos a los que no debes reaccionar son estos [sonido#2,sonido#3, sonido#4, sonido#5]."* |
| EXPERIENCIAL | EXPERIENCIA DEL AULA | VALORACIÓN DE LA PREFERENCIA. |
| POST | | INFORMACIÓN DEL PARTICIPANTE: obtención datos sociodemográficos y niveles de la sensación de presencia. |
| POST | | FINALIZACIÓN. Despedida del participante. |

positivo de RV el aula estímulo. Mientras el sujeto tenía la experiencia inmersiva en el aula virtual, realizaba las tareas de memoria, atención y preferencia consecutivamente. Para llevar a cabo esta última, se muestra una escala de valoración de -4 a 4 en la pizarra del aula virtual. Utilizando esta escala, los sujetos respondieron verbalmente a su nivel de preferencia por el aula visualizada.

En la última fase post-experimental, se recopilaron datos sobre la capacidad de los escenarios para inducir presencia mediante el cuestionario SUS (Slater et al., 1994) y se completaron datos sociodemográficos relevantes. Luego, se finalizó con el participante retirando el dispositivo de RV, entregando las instrucciones finales por pantalla, resolviendo dudas y guiándolo hacia la salida.

## 3. Análisis de datos

Todos los datos obtenidos se tabularon y sistematizaron con el software SPSS (v 27.0). También se usó este mismo software para realizar los análisis descriptivos y estadísticos comparativos, específicos del estudio contemplado en los Capítulos 4 y 5. Por su parte, para el análisis del estudio recogido en el Capítulo 6 se utilizó un modelo matemático de programación lineal multiobjetivo mediante el uso del software Mathematica (v12.1). El conjunto de análisis realizados se recogen en la Tabla 3.

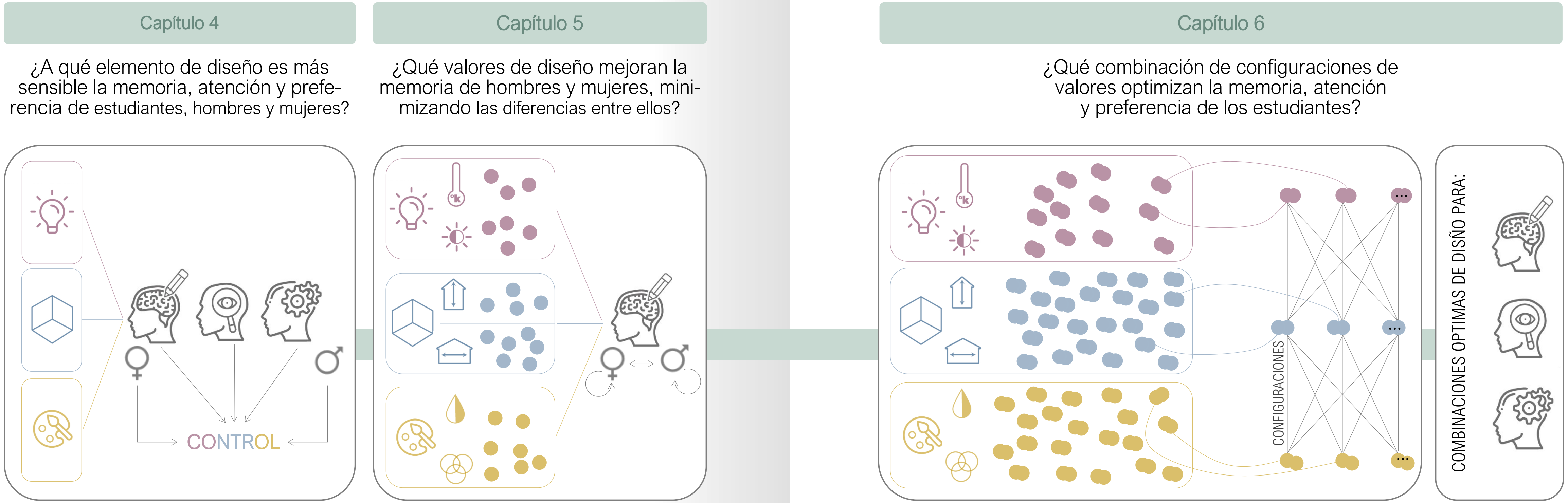
El primer estudio analizó cómo se comportaba la atención, memoria y preferencia de los alumnos ante los cambios, en general, de luz, color y forma del

Tabla 3. Tabla resumen del tratamiento de datos realizado.

| Estudio | Variable dependiente | Variable independiente | Variable de segmentación | Tratamiento de datos |
|---|---|---|---|---|
| 1 | Proceso cognitivo:<br>• Memoria<br>• Atención<br>• Preferencia | Elemento:<br>• Luz<br>• Color<br>• Dimensión<br>• Aula base | Género:<br>• Hombre<br>• Mujer | ANOVA: es una prueba estadística comparativa que se utiliza para evaluar la variabilidad entre tres o más grupos. Determina si las diferencias observadas entre las medias son mayores/menores de lo esperado por azar. |
| 2 | Proceso cognitivo:<br>• Memoria | Parámetros:<br>• Altura de techo (x4)<br>• Ancho del aula (x6)<br>• Saturación del color de las paredes (x2)<br>• Tono del color de las paredes (x5)<br>• Iluminancia (x3)<br>• CCT (x4) | | |
| 3 | Proceso cognitivo:<br>• Memoria<br>• Atención<br>• Preferencia | Combinación de pares de parámetros:<br>• Iluminancia y CCT (3x4)<br>• Altura del techo y ancho del aula (4x6)<br>• Tono y saturación del color de las paredes (10x2) | - | Programación lineal multiobjetivo: procesamiento matemático que datos que permite optimizar simultáneamente múltiples funciones objetivo (nivel de memoria, atención y preferencia) que pueden ser competitivas o contradictorias, a partir de variables de decisión (parámetros de diseño). |

aula. Para ello, se llevó a cabo un análisis comparativo entre la cognición del alumnado en el aula base y las aulas con las diferentes modificaciones. Este análisis se realizó con el conjunto de participantes y segmentando por género (Tabla 3). En el segundo estudio se analizó la memoria del alumnado en aulas diseñadas con diferentes parámetros (un total de 24 parámetros, ver Tabla 3). Se llevó a cabo un análisis comparativo de los niveles de memoria en cada una de las aulas con diferentes parámetros, intra e inter género. Esto implicó analizar la situación por separado para cada grupo de género y luego comparar los resultados entre ellos. En el tercer estudio se optimizaron los niveles de memoria, atención y preferencia del alumnado en función de la combinación de los diferentes pares de parámetros de cada elemento (un total de 46 pares de parámetros, ver Tabla 3). La Figura 6 muestra un esquema representativo de cada una de los estudios recogidos en los capítulos cuatro a seis y que abordan cada uno de los objetivos específicos descritos en el capítulo dos.

Figura 6. Esquema de los estudios realizados. Nótese que las flechas grises indican los análisis realizados.



# Capítulo 4.

## Artículo del primer estudio

El estudio recogido en este capítulo esta publicado como artículo de investigación, siendo su referencia bibliográfica la siguiente: Nolé, M. L., Higuera-Trujillo, J. L., & Llinares, C. (2023). Lighting, colour and geometry: which has the greatest influence on students' cognitive processes?. Frontiers of Architectural Research, 12(4), 575-586. https://doi.org/10.1016/j.foar.2023.02.003

Dicho articulo examina la influencia que los diferentes elementos de diseño de un aula tienen en los procesos cognitivos de memoria y atención de los estudiantes, además de su preferencia por dicha aula. Aborda la sensibilidad que tienen estos procesos a los cambios de los elementos de diseño de dimensión, color e iluminación.

La revista (ISSN 2095-2635) es de alcance internacional y acceso abierto, con un proceso de publicación de revisión por pares (single-blind review). Su contenido contempla logros significativos y pioneros en la investigación arquitectónica, promoviendo estudios respaldados por un enfoque científico riguroso y tecnología avanzada. Sus áreas temáticas incluyen el diseño de espacios, con un enfoque específico en crear entornos que prioricen las necesidades individuales y la experiencia del usuario. En el año 2022 (última anualidad con datos disponible), esta indexada en dos índices internacionales sobre la Calidad de la investigación: SJR (Q1 – FI: 0.592, 35/156, categoría “Architecture”) y JCR (Q1 – JCI: 4.43, 1/97, categoría “ARCHITECTURE - AHCI”).

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

## 1. Introduction

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

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

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

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

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

From a methodological viewpoint, this issue involves a fundamental difficulty, that is, how to modify and analyse individual design elements without changing the remaining elements; the use of physical spaces in this context is problematic because of the high cost of making modifications. Virtual Reality (VR) is an ideal low-cost alternative that allows experimenters to control variables (Latini, 2021). In this regard, Karakas and Yildiz (2020) in a systematic review found that VR is commonly used in subjective perception studies of architectural spaces as it offers simulated environments which appear similar to real environments. The validity of virtual environments has been demonstrated in experiments in which subjects exhibited similar physiological responses and behaviours in both VR and real-life scenarios (Armougum et al., 2019; Higuera-Trujillo et al., 2017; Marín-Morales et al., 2019); in addition, when similar behaviours were exhibited, the participants reported that the VR created a strong sense of presence (Heydarian et al., 2015). In the academic field, similarities in cognitive performance have been demonstrated in real and in VR-based classrooms (Kalantari et al., 2021). Coleman et al.



(2019) demonstrated that working memory training undertaken in a controlled VR environment can subsequently be applied to improve memory function in real world environments. Furthermore, some authors have found that VR is an effective tool for measuring attention performance (Diaz-Orueta et al., 2013; Iriarte et al., 2016) and working memory (Matheis et al., 2007) in learning contexts (Rizzo et al., 2009; Areces et al., 2018). These methodological advances have made it possible to analyse the effects of space in learning contexts.

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

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

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

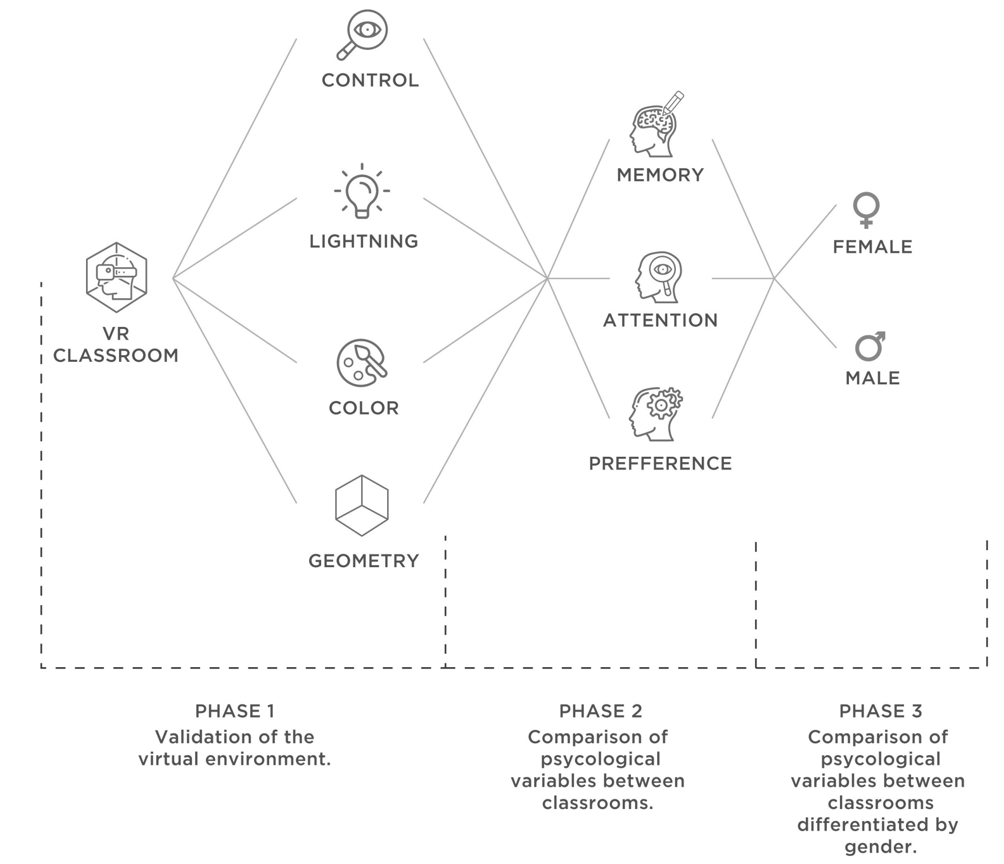
Moreover, the influence of design on human learning may not be equal for males and females. Each person has their own specific cognition and way of interacting with their environment. Research in this field has shown that males and females process the information, including interior design elements,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

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

## 2. Materials and methods

A laboratory experiment was carried out to achieve the objective. Four virtual classrooms were designed, three with different lighting, colour and geometry, and a control classroom. This allowed a comparison to be made between results obtained by subjects in cognitive tests in three modified environments and results obtained in a control classroom. The analysis of the results was carried out in three consecutive phases. First, the virtual simulations carried out were validated (Phase I). Measurements were then taken of the subjects' memory and attention performance and preference for each of the virtual environments (Phase II). Finally, the differences found were quantified and compared based on gender (Phase III). The experimental procedure was conducted in compliance with the Declaration of Helsinki, and was approved by the Review Board (Project P1_25_07_18) of the Polytechnic University of Valencia. Figure 7 shows the general experimental outline.

Figure 7. General methodological schema.



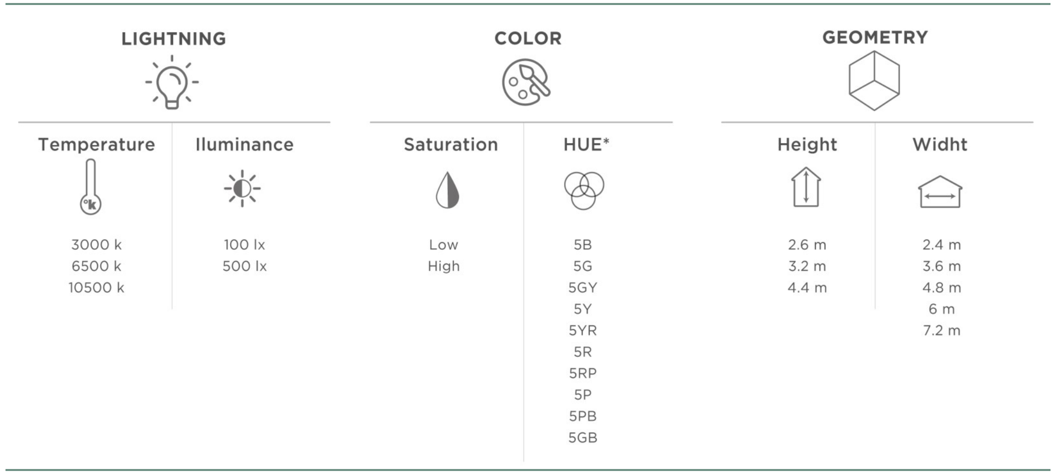
## *2.1. Sample*

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

## *2.2. Stimuli*

The stimuli were virtual reality classrooms. The control classroom was a virtual replica of a room in the Polytechnic University of Valencia, chosen because it is representative of this type of space in Spain. The classroom had the following physical characteristics: neutral white wall colour (N5 in the Munsell colour system), height, width and length typical of classrooms in the university (3.80 m × 8.40 m × 16.50 m) and commonly used artificial lighting (colour temperature of 4000 K, 300 lx of illuminance, and direct flow). The three groups of modifications were based on variations (from the control classroom) of the parameters of the design elements: interior artificial lighting (colour temperature and illuminance); wall colour (saturation and hue); and geometry (height—the clear height from floor to ceiling, and width—the distance between the longitudinal walls). The modification values chosen were based on standard construction criteria (Figure 8). For lighting, the most common bulbs on the market were chosen. For colour, the choice was to use 10 different shades evenly distributed on the Munsell colour wheel, with two saturations always separated by 6 chroma units, and an intermediate constant value of 5 units. For geometry, the choice was to use one of the modules/units frequently employed in the manufacture of flooring and false ceiling parts.

Figure 8. Schema of the parameters analysed: lighting, colour and geometry.




To ensure that other factors had no effect, the position and direction of the lighting, the furniture and its distribution, and other materials and finishes were maintained, as was the location of the subject within the virtual reality classroom (Figure 9).

Figure 9. Set of classrooms visualised as stimuli. The left, middle and right columns show the control classroom characteristics with the modifications corresponding to all possible combinations of the studied parameters of lighting element, colour and geometry, respectively.




### 2.3. Virtual simulation set-ups

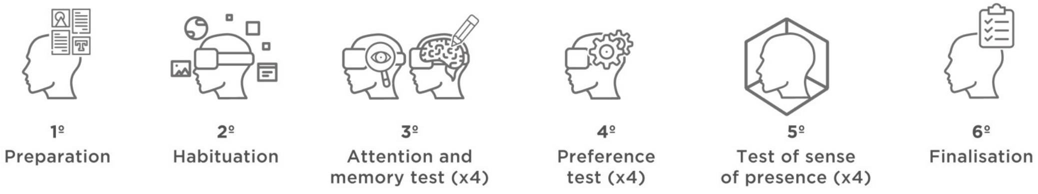
The virtual classrooms were created through a modelling and rendering process. The modelling was carried out using Rhinoceros (v.5.0), and the rendering using V-Ray Renderer (v.3.3), running on Autodesk 3ds Max (v.2014). The renders were configured as 360° panoramas, saved in a JPG format with a resolution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

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

### 2.4. Procedure

The experiment was conducted in a laboratory, always in the same time slot. The procedure consisted of 6 phases (Figure 10).

Figure 10. Experimental procedure: The 6 consecutive steps taken in the research process. The 2nd, 3rd and 4th phases were undertaken using virtual reality.



The total duration of the procedure was 30 min.

In the 1st phase (preparation), the subject was welcomed into the laboratory and the room was prepared for the experiment; instructions were provided to the subjects; the colour vision status of each subject was assessed through the Farnsworth–Munsell Dichotomous D-15 test. Duration: around 5 min.

In the 2nd phase (habituation) the subjects viewed a VR space/room to get them accustomed to the system. This space/room differed "physically" from the four stimuli classrooms used in the experiment: it was of simple design and neutral colours and lighting and had no furniture nor identifying elements. Duration: until the subject considered that (s) he was accustomed to the VR system.

The 3rd phase (attention and memory test) began with the issuing of instructions followed by a 60-s break (during which the subjects did not view any images). Thereafter, the subjects viewed, randomly, for 60 s, one of the virtual classrooms: the control, the lighting-modified, the geometry-modified or the colour-modified classroom. While the subjects were immersed in the virtual classrooms, specific tests measured their levels of memory and attention. To ensure the results did not suffer from response desirability the experimenters explained to the subjects that there were no right or wrong answers. Duration: approximately 15 min.

In the 4th phase (preference test) the subject was immersed in the same classroom, but in this case a rating scale of -4 to 4 was displayed on the classroom's blackboard. Using this scale, the subjects responded to a questionnaire about the classroom in general, and its architectural elements. This phase gathered the subjects' environmental preferences. Duration: about 2 min.

In the 5th phase (test of sense of presence) the subjects removed the HMDs and responded to a SUS questionnaire (Slater et al., 1994) that assessed their level of sense presence in the virtual classrooms. Duration: about 2 min.

In the 6th phase (finalisation) the subjects completed a demographic questionnaire, and the experimental session ended. Duration: about 4 min.



### *2.5. Metrics*

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

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

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

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

### *2.6. Statistical analysis*

The data were analysed using SPSS v. 26.0. The normality of the data was checked by the Kolmogorov-Smirnov test, with the Lilliefors significance correction. The test showed that the data were normally distributed. On this basis, an analysis of variance (ANOVA) was applied. In addition, a descriptive analysis of means was performed to validate the stimuli. All p values $< 0.05$ were considered statistically significant. According to Lakens (2013), the effect sizes were reported with partial eta squared ($\eta^2_p$). Table 4 shows the analyses performed to address the relevant issues.

## 3. Results

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



Table 4. Statistical treatment. Note that, in phase I and II, the variables analysed were: memory (memory hits), attention (speed of correct attention measure responses) and preference (subjective classroom rating score). The means were normalised so that they could be represented on the same axis.

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

### *3.1. Phase I: analysis of sense of presence*

Measures were made of the subjects' average levels of sense of presence for the four classrooms. The results showed values higher than 28, with the mean level of sense of presence in females being higher than in males (31.98 versus 29.06). Based on the results obtained by Slater and Steed (2000), who used the SUS questionnaire with the SUS-total metric, it is reasonable to conclude that the levels of sense of presence obtained were satisfactory. Figure 11 depicts the average levels of sense of presence for the four scenarios.

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

Following the validation of the VR environment, statistical techniques were used to compare the responses to the different design elements, lighting, colour and geometry, with responses to the control room. Given the normality of the variables, an ANOVA test was applied. The results are shown in Figure 12.

Working memory metric. The control classroom returned the poorest results. Modified lighting significantly improved the results ($F_{(1,682)}$ =6.304, p = 0.012, $\eta^2_p$ = 0.009). While geometry and colour modifications did improve performance in the memory test, the results were not significant (p > 0.05).

Sustained attention metric. Again, the worst results were obtained in the control classroom, where reaction times were the longest, thus attention paid was the poorest. Reaction time was significantly reduced, that is, improved, by classroom interventions in lighting ($F_{(1,613)}$ = 5.230, p = 0.021, $\eta^2_p$ = 0.009), colour ($F_{(1,562)}$ = 3.434, p = 0.027, $\eta^2_p$ = 0.006) and geometry ($F_{(1,835)}$ = 4.898, p = 0.023, $\eta^2_p$ = 0.006), which demonstrates the sensitivity of the cognitive function attention to classroom design.

Environmental preference metric. Again, the worst results were obtained in the control classroom. As with memory, interventions in colour and geometry did not significantly improve the results (p > 0.05). Lighting modifications, however, significantly (F(1,679) = 16.68, p < 0, $\eta^2_p$ = 0.024) improved the results.



Figure 11. Average level of sense of presence in each simulated classroom type.

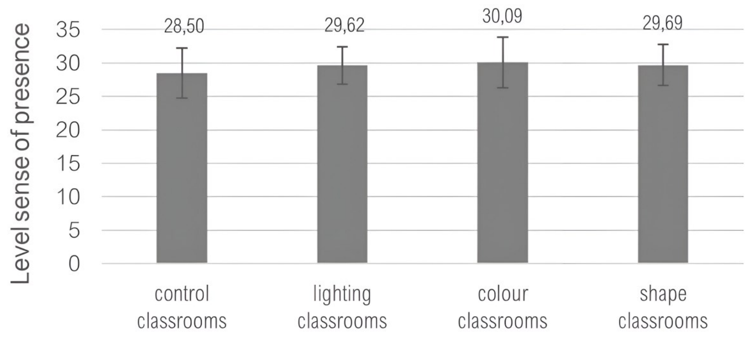
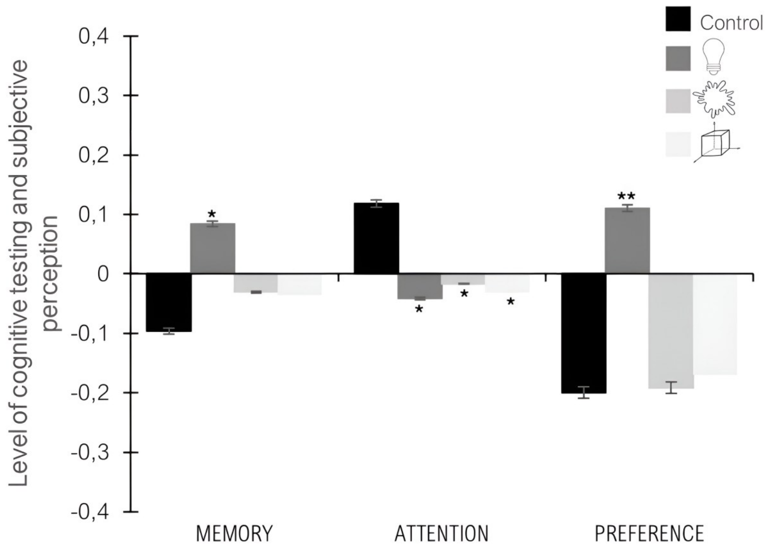



Figure 12. Relationship between subjects' psychological metrics and classroom design elements. The asterisks indicate significance levels (*p < 0.05, **p < 0.01).



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

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

To analyse differences due to gender, the same analysis as carried out in Phase II was conducted, but this time segmenting the responses between males and females. Figure 13 shows the results obtained.

Working memory metric. Lighting improved the test results, as was the case in Phase II, but the improvement was only significant ($F_{(1,310)}$ = 6.06, p = 0.014, $\eta^2_p$ = 0.019) in the male group.

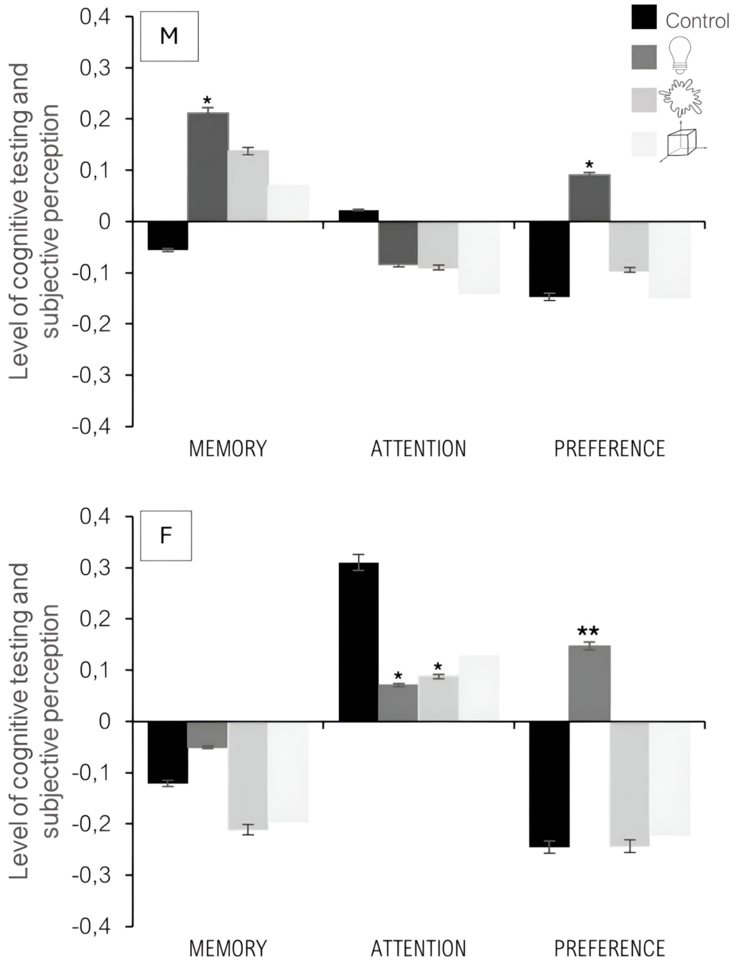
Sustained attention metric. While design interventions did improve results in the male group, the enhancements were not significant (p > 0.05). However, for the female group, changes in lighting and colour significantly reduced reaction times ($F_{(1,301)}$ = 5.507, p = 0.020, $\eta^2_p$ = 0.018; $F_{(1,259)}$ = 4.254, p = 0.040, $\eta^2_p$ = 0.016, respectively). While geometry was not shown to be significant, it was close to significant (p < 0.075) for both genders.

Environmental preference metric. For both genders, lighting significantly improved ($F_{(1,310)}$ = 5.085, p = 0.025, $\eta^2_p$ = 0.016 for males; $F_{(1,325)}$ = 12.379, p < 0.000, $\eta^2_p$ = 0.037 for females) the ratings.

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



Figure 13. Relationships between the subjects' psychological variables (M: male and F: female) and the design elements of the classrooms. The asterisks indicate the significance levels (*p < 0.05, **p < 0.01).



## 4. Discussion

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

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

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

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

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

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

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

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

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

## 5. Conclusions

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

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

# Capítulo 5.

## Artículo del segundo estudio

El estudio recogido en este capítulo esta publicado como artículo de investigación, siendo su referencia bibliográfica la siguiente: Nolé, M. L., Higuera-Trujillo, J. L., & Llinares, C. (2021). Effects of classroom design on the memory of university students: from a gender perspective. International Journal of Environmental Research and Public Health, 18(17), 9391. https://doi.org/10.3390/ijerph18179391

Dicho articulo esta centrado en abordar cómo la memoria de los estudiantes hombres y mujeres se ve influida por diferentes elementos de diseño del aula. Profundiza en la diferencia de memoria entre ambos géneros ante diferentes diseño de un aula.

La revista (ISSN 1660-4601) es de carácter internacional, transdisciplinaria, revisada por pares (siguiendo una single-blind review) y de acceso abierto. Se centra en contenido relacionado con la promoción de la salud y la mejora de la calidad de vida, reuniendo a todas las comunidades científicas de diversas disciplinas. Entre sus áreas temáticas se encuentra la interacción: seres humanos y entornos físicos, lo cual se alinea con el objetivo amplio de estudiar la influencia del ambiente en la cognición humana. En el año 2021 (anualidad de publicación del artículo), estaba indexada en los índices SJR (Q1 – FI: 0.814, 34/140, categoría “Health, Toxicology and Mutagenesis”) y JCR (Q1 –JCI: 4.614, 45/182, categoría “PUBLIC, ENVIRONMENTAL & OCCUPATIONAL HEALTH - SSCI”).

Abstract. Classroom design has important effects on the cognitive functions of students. However, this relationship has rarely been analysed in terms of gender. The aim of the present study, therefore, is to analyse the influence of different design variables (classroom geometry, wall colour, and artificial lighting) on university students' memories from a gender perspective. To do so, 100 university students performed a memory task while visualising different design configurations using a virtual reality setup. Key results show that certain parameters, such as 5.23 m classroom width, 10,500 Kelvin lighting colour temperature, or the blue hue on the walls influence men and women in a similar way, while a purple hue or walls with low colour saturation can generate significantly different behaviour, especially in cognitive processes such as short-term memory. In this study, the use of virtual reality proved to be a useful tool to explore the design effects of virtual learning environments, increasingly present due to training trends and catalysed by the 2020 pandemic. This is a turning point and an international novelty as it will enable the design of classrooms (both physical and virtual) that maximise the cognitive functions of learners, regardless of gender. Keywords: classroom design; learning processes; memory; gender; psychological responses; virtual classroom.

## 1. Introduction

Most academic research in education has been focused on studying how to foster the internal aspects of students to improve their learning levels. Specific actions such as including family participation in the classroom (Gutiérrez-Fresneda, 2019), or the use of inverted methodology (Van Alten et al., 2019)—where students must study the content of the subject before class—promote learning to read and improve school performance, respectively. However, the reality is that learning is a very complex process influenced by many factors (Beltrán-Velasco et al., 2021; Helal et al., 2018).

In this sense, there are far fewer studies that analyse classroom-contextual influences on the learning process. Although it is known that the configuration of the classroom, such as its layout or other elements of its design, relates to different cognitive (Choi et al., 2014) and emotional processes (Evans & Stecker, 2004; Yang et al., 2013) few efforts have emerged to address these issues with respect to the existence of studies focused on understanding the influence of internal subject factors or teaching methods within a classroom.

This is of particular interest today as the 2020 pandemic steeply raises the importance of virtual learning (VR) environments. In recent months, the configurations of many classrooms have been greatly altered. The need for bubble groups in schools has forced a complete change in the distribution of furniture, and students have had to change their location with respect to other classmates, making use of new spaces that were initially created for other purposes, such as libraries or sports halls. Thus, it seems necessary to look more closely at the relationship between the physical learning environment and the students' response to it.

Of all the design elements that make up the classroom, the environmental variables (temperature, acoustics, and lighting) have been the most studied. Studies such as that of Choi et al. (2014) found that temperature and air quality were the most important contextual determinants of learning. In terms of acoustics, it has been found that the farther from the sound source and the greater the presence of noise, the greater the negative impact on the learning process (Crandell & Smaldino, 2000; Picard & Bradley, 2001). Lighting has also been extensively studied for its involvement in physiological processes at the neurotransmitter level (Rea et al., 2002) and biological processes such as the regulation of circadian rhythms in humans (Turner et al., 2010). For example, the presence of natural light has been identified as positively influencing reading and science activities (Heschong et al, 2002; Tanner, 2009). In addition, the level of lighting affects cognitive performance depending on the difficulty of the task presented (Huiberts et al., 2015).

Another well-studied visual variable has been colour, because of its clear impact on students' emotions and functionality (Barrett et al., 2013; Choi et al., 2014). Authors such as Nancy Kwallek have shown that more errors are made in reading and writing tasks in white spaces compared to coloured spaces (Kwallek et al., 1996). However, there seem to be inconsistencies as to which colours generate better performance. Some authors relate differences to the age of the students (Barrett et al., 2013, 2015; Mahnke, 1996), others point to the importance of task content (Xia et al., 2016), whilst a third group highlights the role of arousal in this interaction (Hamid & Newport, 1989; Walters et al., 1982).

Finally, it is important to refer to the dimensions and geometry of a classroom, which is undoubtedly the least studied aspect (Read et al., 1999). The lack of studies that concretely analyse this variable makes it difficult to take a clear position on its importance. However, among those that have been carried out, it has been shown that classrooms with high ceilings have an impact on learning as they negate the benefit of better lighting as well as increasing acoustic problems due to reverberation (Earthman, 2004).

In all cases, it is noteworthy that each of the spatial elements is approached in isolation, offering results that are not very decisive, as they do not take into account the integrated set of variables that contribute to the characteristics of the space. For this reason, studies are needed to analyse how several design variables can affect the cognition of the individual, making it possible to detect those that have a greater effect on their behaviour. Some studies have been based on contextualised points of interest through tasks of an attentional nature, with little consideration given to working memory, which is very much involved in the process of cognitive performance. Moreover, it is also important to note that research in this area does not pay much attention to the characteristics of the subject. The age of the subject is crucial given that learning is a continuous developmental process that varies over time (Lejeune et al., 2013). Most studies focus on basic education at an early age, neglecting developments that may happen in higher education at the university level.

Yet another variable to be studied that is specific to the student is gender. Men and women show many differences in environmental perception in terms of colour preference (Fortmann-Roe, 2013) or sensitivity to glare in classroom lighting (Yang & Jeon, 2020). Igor Knez (2001) found that long-term memory performance differed with respect to gender depending on the type of ambient lighting. Additionally, Hartstein et al. (2018) found an improvement in executive functions occurring with a higher level of lighting colour temperature. Physically, it is the temperature at which a black body should be heated to emit a certain colour of light. The lighting colour temperature is usually expressed in kelvins (K). At low temperatures the body would emit a light close to red (warm), and as the temperature increases it would be white (neutral) and later blue (cool). Although these gender differences are known, there has been little analysis of the interior of a classroom design from this perspective.

From a methodological point of view, there is an important limitation in the reviewed studies regarding the stimuli used, as they generally employ physical spaces (Barrett et al., 2015; Marchand et al., 2014; Yildirim et al., 2015). Physical spaces have the problem of fixing one aspect of the design. An extensive review of the application of virtual reality in research of sensory and perceptual science suggests VR as a good alternative (Crofton et al., 2019). There are studies that validate its use to generate and analyse different configurations of colour (Llinares et al., 2021a) and geometry (Llinares et al., 2021b). These control an adequate level of sensation of presence for the subject, known as the “perceptual illusion of non-mediation” (Lombard & Ditton, 1997). There are already numerous other studies that use VR to develop cognitive tasks that analyse aspects of attentional processes (Díaz-Orueta et al., 2014; Iriarte et al., 2016; Rizzo et al., 2009), or to train children with attention-deficit/hyperactivity disorder (Rodríguez et al., 2018).

Based on the aspects detailed so far, the objective of this work is to analyse the impact that certain elements of classroom design—specifically room geometry, wall colour, and interior lighting—have on the memory of university students from a gender perspective. Memory is an important factor for academic performance. It is involved in the encoding and decoding of information. There is evidence that contextual factors such as lighting can especially affect short-term memory in virtual spaces (Llinares et al., 2021c), but also findings of a relationship between these variables in physical spaces (Hygge & Knez, 2001; Xiong et al., 2018; Yang & Jeon, 2020). Therefore, other factors could also be influencing this type of memory. Knowing this relationship would allow us to identify the design elements that positively or negatively affect the memory levels of female and male students, and inform the design of a classroom that benefits both genders.

## 2. Materials and Methods

To address the objective of the study, a laboratory experiment was conducted. It consisted of exposing participants to different experiences of a virtual classroom, modified in a controlled manner consisting of three variables: the geometry of the room; the colour of the walls, and artificial lighting. This was validated by quantifying the level of presence (Slater & Steed, 2000) of the virtual experiences (Phase I). In each virtual classroom, memory performance was measured for the female group (Phase II) and the male group (Phase III). Finally, the results of both groups were compared (Phase IV). Figure 14 shows the general methodological scheme.

### *2.1. Sample*

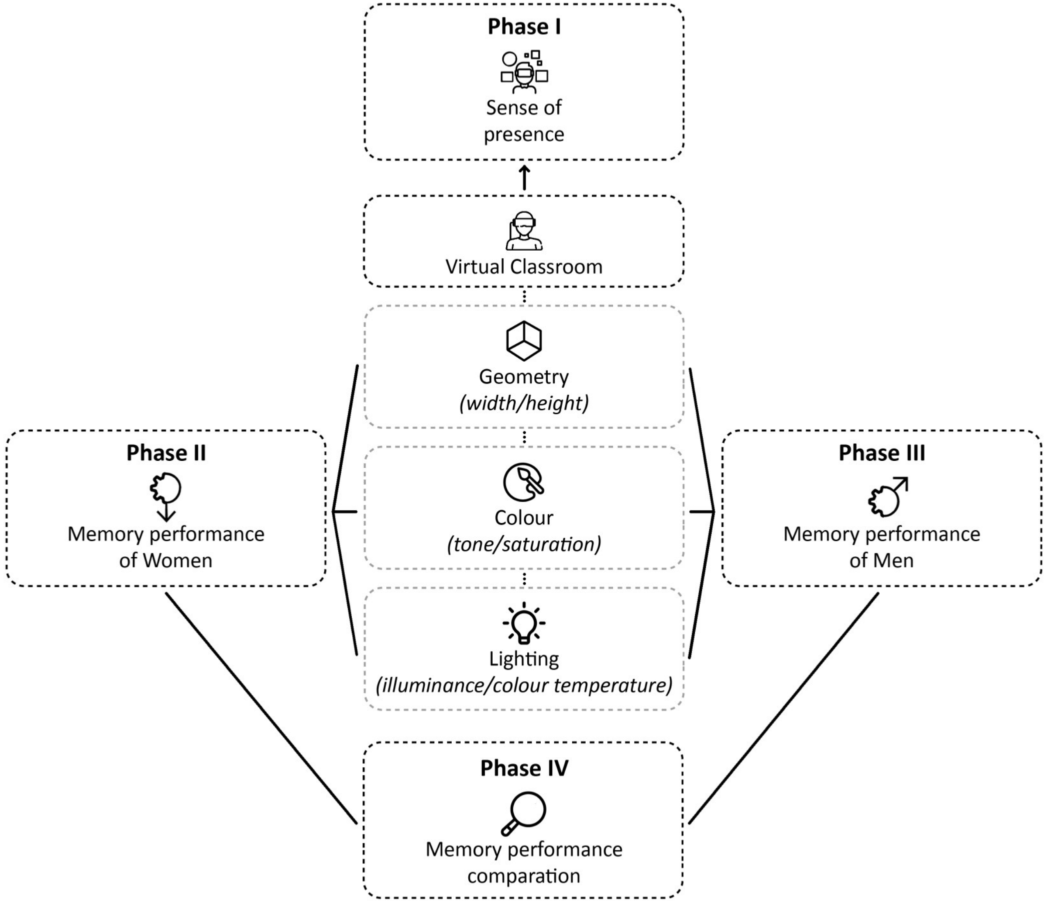
A total of 100 participants were recruited for the experiment (mean age = 23.24 years; $\sigma$ = 3.79). Care was taken to ensure that the sample was gender balanced: 50% male and 50% female. The primary inclusion criterion was to be a university student. In addition, two further conditions were established: (1) having Spanish nationality (to control for cultural variation); and (2) having normal or corrected-to-normal vision through contact lenses (avoiding spectacles given problems with usage of the VR device). Prior to the start of the experiment, all participants were duly informed of its workings after which they signed a consent form. The study was supervised by the Ethics Review Committee of the Institute for Research and Innovation in Bioengineering, at the Polytechnic University of Valencia, in compliance with the Declaration of Helsinki.

### *2.2. Stimuli*

A classroom of the School of Building Engineering of the Polytechnic University of Valencia was chosen to be virtualised. The selection criterion was based



Figure 14. General methodological scheme



on it being typical of the physical teaching spaces of the university. The virtual replica became the base classroom for subsequent variation. Modifications concerning room geometry, wall colour, and artificial lighting were then applied to it through the compensated change of the values of their respective parameters.

In the geometry variable, the parameters of height and width were considered. Specifically, six different measures of width and four of height were applied. These measures were based on a stepped increase or decrease in the original value by 1.2 m. The combination allowed for 24 geometrical modifications of the classroom (4 × 6, including the measurements of the base classroom). The length of the classroom was not modified.

For the colour variable, the parameters of hue and saturation were considered. The selection control was carried out using the Munsell notation system. Specifically, five hues equally distributed on the Itten colour circle (Itten, 1986), for each of which two saturations (high and low) were taken, separated by six Munsell chroma units. In combination it was then possible to obtain 10 modifications of the classroom (5 × 2, not including the measurements of the base classroom, because its colour was desaturated).

As for the lighting, both illuminance and colour temperature parameters were considered. Specifically, three luminance levels (being lower and higher than the value of the base classroom) and three colour temperature values (corresponding to values typically found on the market). The combination of these allowed 12 classroom modifications to be made (including the measurements of the base classroom).

It should be noted that each modification was applied separately to the base classroom, so the original parameters of the other two variables were kept constant. The combinations resulted in an array of classroom modifications that was administered to the participants. Each participant viewed four classrooms: the base, and three randomly modified virtual ones. Each virtual classroom was viewed from eight to nine times in total. Figure 15—17 describe the characteristics of each virtual classroom.



Figure 15. Virtual classrooms modified in geometry.

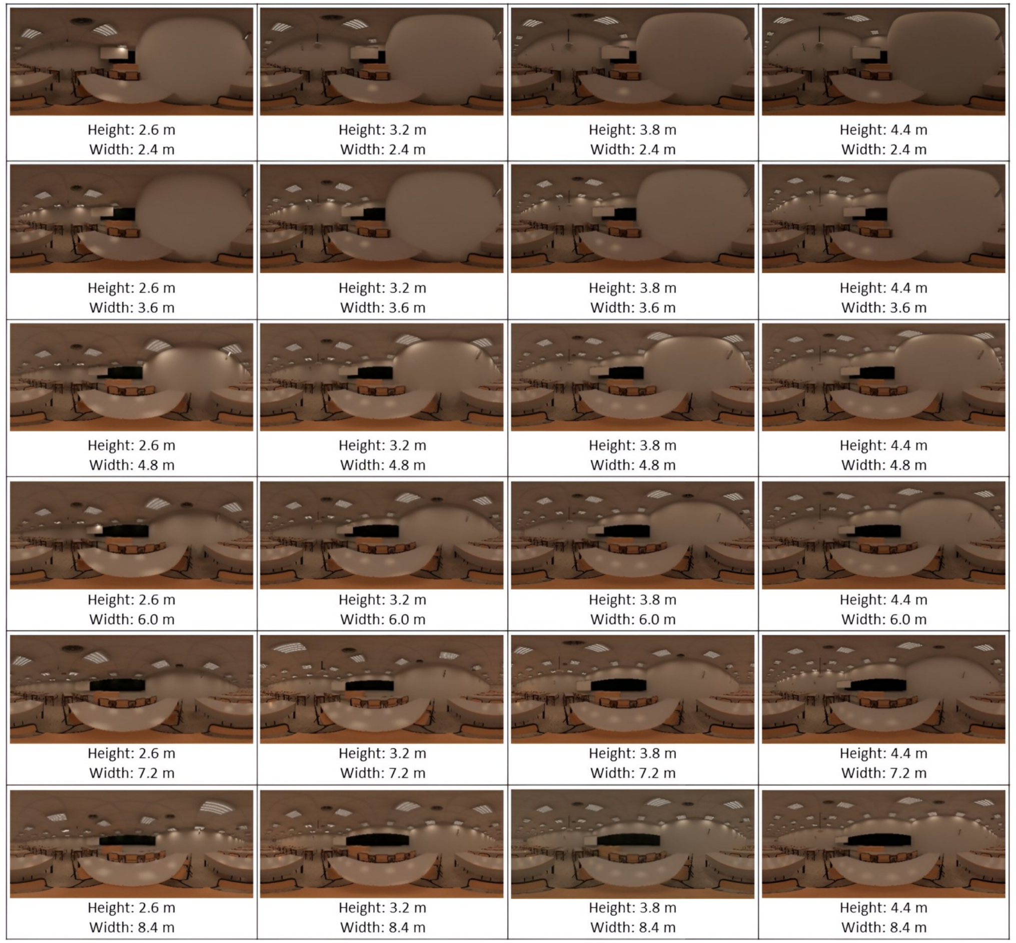
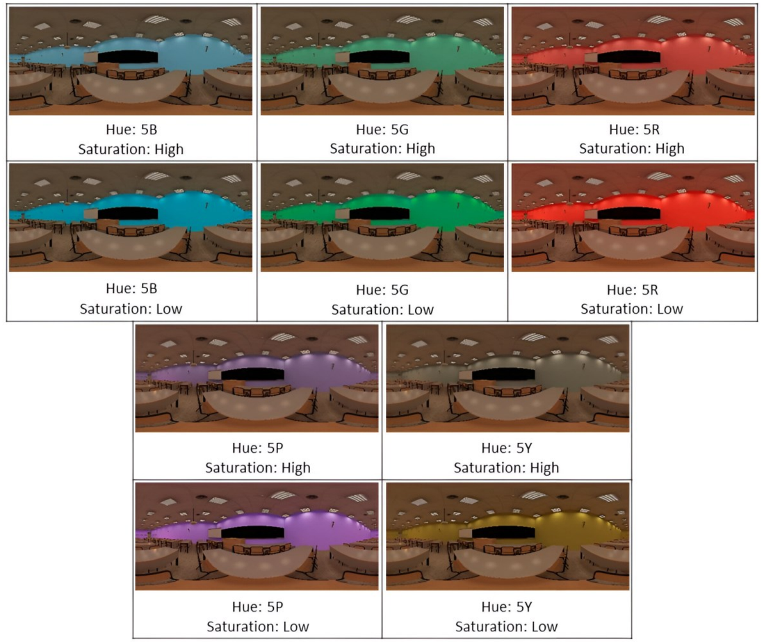


Figure 16. Virtual classrooms modified in colour.



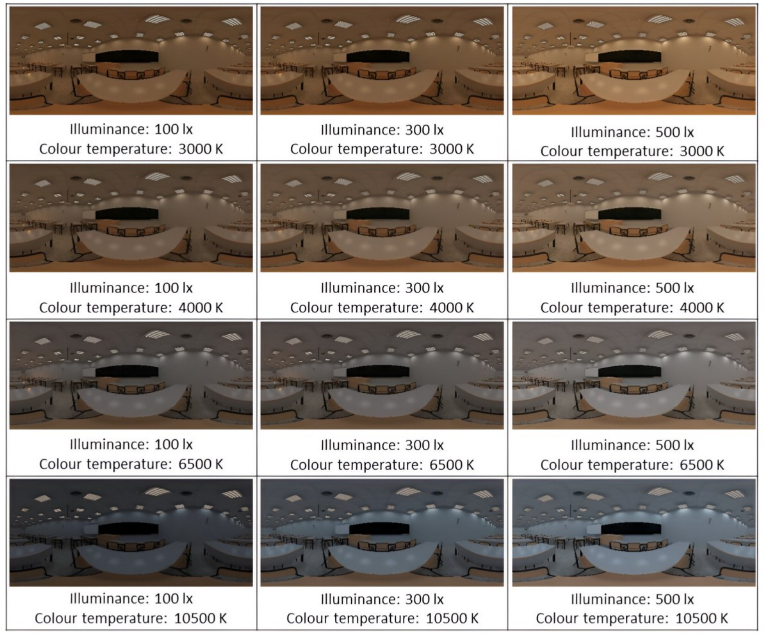

## *2.3. Scenario*

Participants experienced the virtual classrooms through VR simulations on head-mounted displays (HMDs).

The VR classroom simulations were generated through a process of 3D modelling and rendering. For this, two main software packages were used: Rhinoceros (v.5.0, Robert McNeel & Associates, Seattle, WA, USA), and the Corona Renderer engine (v.2.0, Corona Renderer, Czech Republic, European Union). The colours of the walls studied were determined in the Munsell notation system, so for the virtual representation it was necessary to use ColorMunki$^{TM}$ (X-Rite, Grand Rapids, MI, USA) to translate the five colours studied into RGB notation.



Figure 17. Virtual classrooms modified in lighting.




A head-mounted display (HTC Vive device) connected to the experimenter's computer was used to simulate the classroom. Unity3D (v5.6, www.unity3d.com, accessed on 1 December 2004) was used to generate the software, which allowed the experimenter to show the different scenarios that the participant could then see through the HTC Vive. All the individual visualisations of the scenarios presented were identical. The subjects began the simulation, all seated at the same point in the classroom in the centre of the second row of tables. The participants could not get up and move around the room, but they could change the visual trajectory by means of head movements that allowed them to inspect the space. The corresponding memory test required wired speakers, which were calibrated before each session to ensure sound consistency.

### 2.4. Experimental Protocol

All experimental sessions were strictly conducted according to a protocol, always in the same room of the laboratory. The experimenter and participant were sat in opposition, each with their corresponding table, chair, and screen. The participant wore the HMD calibrated to the relevant environment. The experimenter's position consisted of the computer from which the different virtual reality scenarios were launched and the memory test lists played. Attempts were made to control extraneous variables by running all experimental sessions during the same time period on each day. The experimenter tried to keep the level of acoustic isolation, the room temperature, and the furniture arrangement in the room unchanged. In addition, the devices used were the same for the whole sample. Table 5 shows the different actions carried out during the experimental protocol. Here it can be seen that actions B.2 to B.5 are repeated four times: first for the base virtual classroom, and then for three modified virtual classrooms.

### 2.5. Measurement

Data were collected from each participant in the virtual classroom to quantify firstly a sense of presence, and secondly, memory performance.

Sense of presence is defined as the feeling of being immersed in the VR and it not being perceived as artificial. For its evaluation, participants completed the SUS questionnaire (Slater et al., 1994), based on six items rated on a Likert-type scale (1–7). A quantification of presence was performed for each visualisation, by means of a "SUS-Total" metric. This questionnaire has been widely used to study and quantify the sense of presence of participants experiencing an environmental simulation using the same technology (Usoh et al., 2000). For every participant, the results of the six items were then totalled in each virtual classroom (out of a maximum of 42 points: 6 items × 7 points), to quantify the sense of presence of each visualisation. This resulted in the "SUS-Total" metric.

The memory task consisted of an instruction to memorise a set of words. Specifically, lists of 15 audible words using Loquendo TTS 7 (www.loquendo.com, accessed on 1 December 2004), were played on the same personal computer at



Table 5. Experimental protocol.

| | | |
|---|---|---|
| A. Preparation | | **A.1. Welcome of the participant:** Reception of the participant, information about the procedure, signing of documents, and resolution of doubts. |
| | | **A.2. Visual colour perception test:** Administration of the Farnsworth–Munsell Dichotomous D-15 test, to detect possible problems in colour vision. |
| | | **A.3. VR test:** Placement of the virtual reality device, and presentation of a neutral scenario (different from the stimulus) to settle the participant's habituation, and any further problem solving. |
| B. Experimental | | **B.1. Initiation of the experimental phase:** Administration of instructions on the start of the experimental phase via the computer screen. After this, final positioning of the virtual reality device. |
| | For each Virtual Classroom | **B.2. Relaxing audio:** Administration of natural sounds for 60 s, to promote a state of relaxation and reduce the participant's mental fatigue. |
| | | **B.3. Virtual classroom:** Visualisation of the virtual classroom for 90 s. |
| | | **B.4. Memory assessment:** Administration of the memory task, and quantification of the number of correctly recalled words (Memory-Correct Answers metric). |
| C. Post-Experiment | | **C.1. End of the experimental phase:** Final removal of the virtual reality device, followed by administration of the instructions on the end of the experimental phase via the computer screen. |
| | | **C.2. Demographic data:** Completion of a basic demographic questionnaire. |
| | | **C.3. Participant's farewell:** Informing of the end of the process, resolution of any doubts, and indication of the exit. |

the same volume level. The words were related by a common concept, but that concept was excluded from the list. Immediately after listening, subjects had to recall their maximum number of words within a time limit of 30 s. This is similar to the Deese, Roediger, and McDermott (DRM) paradigm experiments (Beato & Díez, 2001). The task was repeated three times for each presentation with an interval of 2000 ms, but the words in each list were different. The order of presentation was randomised among a total of 12 different types of lists (four virtual classroom displays by three attention tasks during each display). Visual tasks were not used because it might interfere with the aim of the study on the effects of spatial configurations of an interior on academic performance, as it also requires the visual pathway. After testing, for every participant the memory performance was quantified as the total number of words correctly recalled in each virtual classroom (out of a maximum of 45 words: 15 words × 3 lists) based on Alonso et al. (2004). This resulted in the "Memory-Correct Answers" metric.

### 2.6. Data Analysis

Table 6 shows the analysis performed and the expected results for each Phase. IBM SPSS software was used (v.17.0, IBM, Armonk, NY, USA). The analysis of the level of sense of presence (Phase 1) was performed by summing the average level of the six items that compose the SUS questionnaire. The analysis of the effect of the different configurations of geometry, colour, and lighting on the memory of female (Phase 2) and male (Phase 3) students was carried out using statistical comparison techniques. The response of the students was compared to different categories of the design variables. This made it possible to identify differences and, if they existed, which design configuration was associated with higher or lower performance. In the same way, statistical comparison techniques were also applied to analyse the effect of classroom design on students' memory as a function of gender (Phase 4). Thus, the incidence of each design configuration on memory was compared between male and female students. This analysis made it possible to identify significant differences between both genders. For the selection of these comparative statistical techniques, the criterion for performance normality of memory was verified using the Kolmogorov–Smirnov (K-S)



Table 6. Statistical treatments.

| Phase | Analysis | Statistical Treatment | Expected Result |
|---|---|---|---|
| Phase 1. Validation of the VR environment. | Analysis of level of sense of presence: SUS-Total. | Descriptive analysis of means. | Sufficient level of presence. |
| Phase 2. Effect of classroom design on the memory of female students. | Analysis of memory performance (women), by modifying the shape, colour and lighting of the classroom: Memory-Correct answers (women) | ANOVA and Bonferroni's post-hoc analysis (normally distributed data) for memory hits, according to the different categories of the design variables. | Significant differences in memory performance, depending on the classroom design. Identification of the design which gave the best and the worst memory performance, for the women's group. |
| Phase 3. Effect of classroom design on the memory of male students. | Analysis of memory performance (men), by modifying the shape, colour, and lighting of the classroom: Memory-Correct answers (men) | ANOVA and Bonferroni's post-hoc analysis (normally distributed data) for memory hits, according to the different categories of the design variables. | Significant differences in memory performance, depending on the classroom design. Identification of the design which gave the best and the worst memory performance, for the men's group. |
| Phase 4. Comparative analysis of the effect of classroom design on students' memory as a function of gender. | Comparative analysis of memory performance for each configuration by gender. | ANOVA and Bonferroni's post-hoc analysis (normally distributed data) for memory hits, according to gender. | Significant differences in memory performance, relating to their gender |

test. This test determined a normal distribution of data (significance level > 0.05), so the statistical technique of analysis of variance (ANOVA) was applied. When the configurations to be compared had more than two categories, the Bonferroni post-hoc analysis was applied to identify the differences between them.

## 3. Results

The design effect was studied at the level of design parameter configuration (grouped with the other parameter of the same design variable), and not each combination independently. Therefore, 24 parameters of the variables geometry, colour, and lighting were studied (Table 7), which were combined to create the configurations shown in Figure 18—21. The statistical analysis of the data produced the following results.

Table 7. Set of parameters studied.

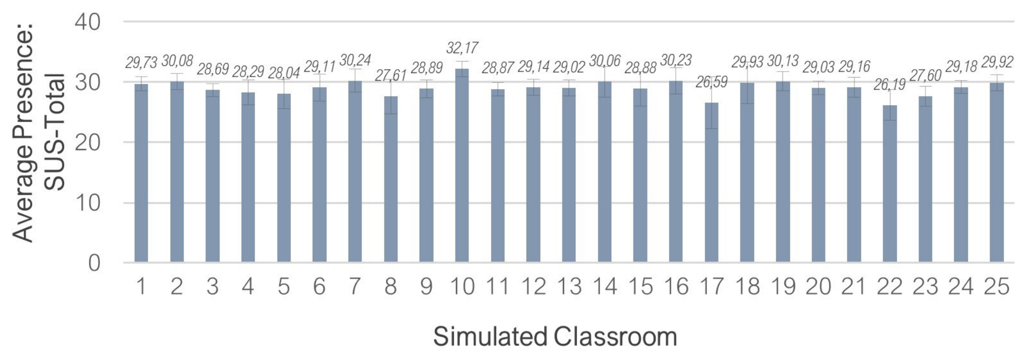
| Geometry | | Colour | | Lighting | |
|---|---|---|---|---|---|
| Ceiling Height | Classroom Width | Saturation | Hue | Colour Temperaure | Illuminance |
| 2.6 m<br>3.2 m<br>3.8 m<br>4.4 m | 2.4 m<br>3.6 m<br>4.8 m<br>6 m<br>7.2 m<br>8.4 m | Low<br>High | 5P<br>5R<br>5Y<br>5G<br>5B | 3000 K<br>4000 K<br>6500 K<br>10,500 K | 100 lx<br>300 lx<br>500 lx |

### *3.1. Phase I. Analysis of Level of Sense of Presence*

Mean levels of sense of presence per participant (based on the SUS questionnaire with the SUS-Total metric) were obtained for each environmental simulation. Taking into account the results obtained by studies using similar technologies (Slater & Steed, 2000), the presence levels were considered satisfactory. Figure 18 shows the average level of sense of presence for each simulated classroom.



Figure 18. Average level of presence for each simulated classroom.




### *3.2. Phase II. Effect of Classroom Design on the Memory of Female Students*

In the following, the impact of design variations in shape, colour, and lighting on the performance of the memory task is analysed for female university students. In the psychological memory task, the Memory-Correct Answers metric was used. This quantifies the number of words recalled in the psychological memory task. Simply put, the more words recalled, the better the memory performance. Due to the normality of these data (K-S, $p > 0.05$), an ANOVA was applied. Figure 19 shows the normalised means for the set of configurations analysed.

Effect of Variations in Classroom Shape (Ceiling Height and Classroom Width). The ANOVA found no significant differences in memory task performance when changing the ceiling height ($p < 0.05$). However, they did occur when varying the width of the classroom ($p = 0.002$), with a significant decrease in memory-task performance when reducing the width of the classroom. Thus, a relevant change was observed with measurements of less than 7.2 m. The worst result in the memory test corresponded to a width of 3.6 m. A Bonferroni post-hoc analysis showed that this difference occurred between 3.6 m and the measurements of 7.2 m (p = 0.048).

**Effect of Variations in Classroom Colour (Hue and Saturation).** Classroom colour saturation was shown to significantly influence memory task performance for female students (p = 0.023). Accordingly, ANOVA showed significantly higher results for higher saturations. Additionally, the hues of the classroom coverings generated significant differences in the memory test (p = 0.000). The best result was observed with the 5B (blue) hue and the worst performance with the 5Y (yellow) and 5P (purple) hues, demonstrating significant differences between them (5B vs. 5Y and 5B vs. 5P) (p = 0.000).

**Effect of Variations in Classroom Lighting (Colour Temperature and Illuminance).** The colour temperature of the lighting was also an element affecting memory, with significant differences depending on the colour temperature (p = 0.000). It was observed that the higher the colour temperature, the better the memory task performance. However, this relationship reached a turning point between 6500 and 10,500 K, where the memory test result then decreased significantly. Thus, the best result corresponded to the colour temperature of 6500 K, while the worst result was for 10,500 K. The Bonferroni post-hoc analysis showed significant differences between the lowest and highest colour temperatures (3000 vs. 6500 K, p = 0.001; 3000 vs. 10,500 K, p = 0.033; 4000 vs. 6500 K, p = 0.000; 4000 vs. 10,500 K, p = 0.012) and between the two highest colour temperatures, between which there was a change in trend (6500 K vs. 10,500 K, p = 0.000). Illuminance, however, did not influence the results of the memory test.

### *3.3. Phase III. Effect of Classroom Design on Male Students' Memory.*

This section analyses the effect that design variations have on memory test performance for males. Again, we use the Memory-Correct Answers metric, which quantifies the number of words remembered in the psychological memory task. Due to the normality of these data (K-S, p > 0.05), an ANOVA was applied. Figure 20 shows the normalised means obtained for the set of configurations analysed.



Figure 19. Standardised means of the psychological memory task for women, Memory-Correct Respon-ses for women.

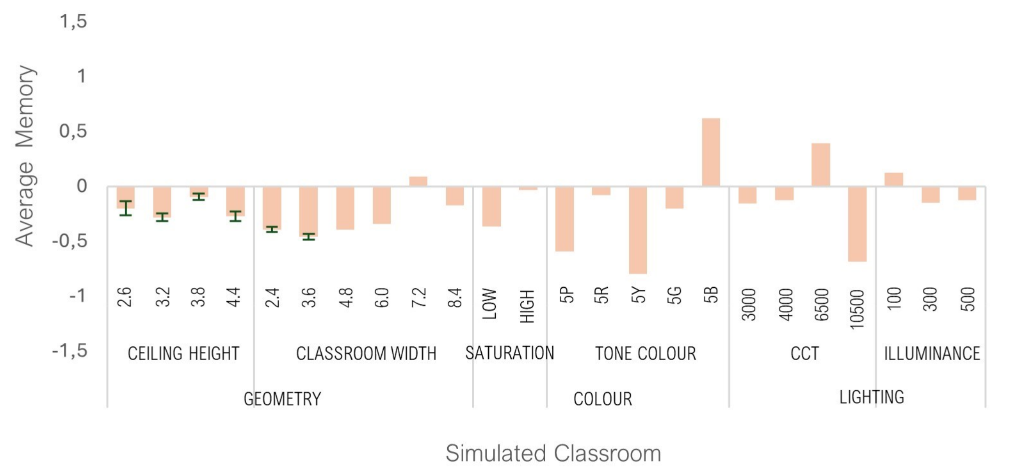
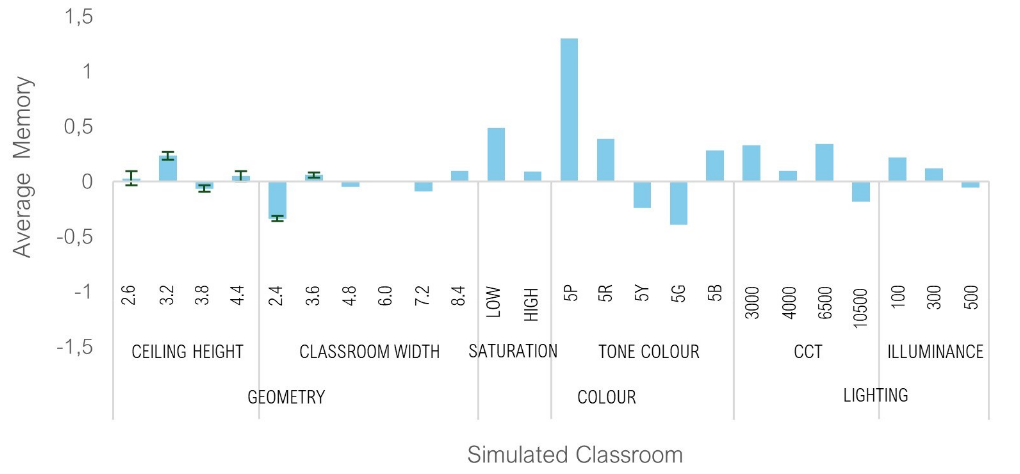



Figure 20. Normalised means of Memory-Correct Answers in men's sample.



Effect of Variations in Classroom Shape (Ceiling Height and Classroom Width). ANOVA showed that there was no significant difference in memory task performance when modifying ceiling height ($p < 0.05$). However, the width of the classroom did seem to be a determining factor in the memory test, as the ANOVA identified significant differences in the results obtained in the memory test when varying the width of the classroom ($p = 0.024$). The best result corresponded to the dimensions of 8.4 m, while the worst performance was obtained with a width of 2.4 m.

Effect of Variations in Classroom Colour (Hue and Saturation). Classroom colour saturation did not influence memory task performance for male students ($p = 0.023$). Higher mean values were found for low saturations versus high saturations. Nevertheless, hue variations did generate significant differences in the memory test ($p = 0.000$). The best results were observed with the 5P (purple) hue and the worst with the 5G (green) and 5Y (yellow) hues, with significant differences between them (5P vs. 5G and 5P vs. 5Y) ($p = 0.000$).

Effect of Variations in Classroom Lighting (Colour Temperature and Illuminance). The colour temperature of the lighting had a significant effect on memory test performance ($p = 0.022$). In this case, positive results were observed for lighting colour temperature values between 3000 and 6500 K, but there was a negative result when moving to 10,500 K. The Bonferroni post-hoc analysis showed an inflection point when going from 6500 to 10,500 K ($p = 0.043$), similarly in the case of women. The illuminance did not influence the results of the memory test for this group.

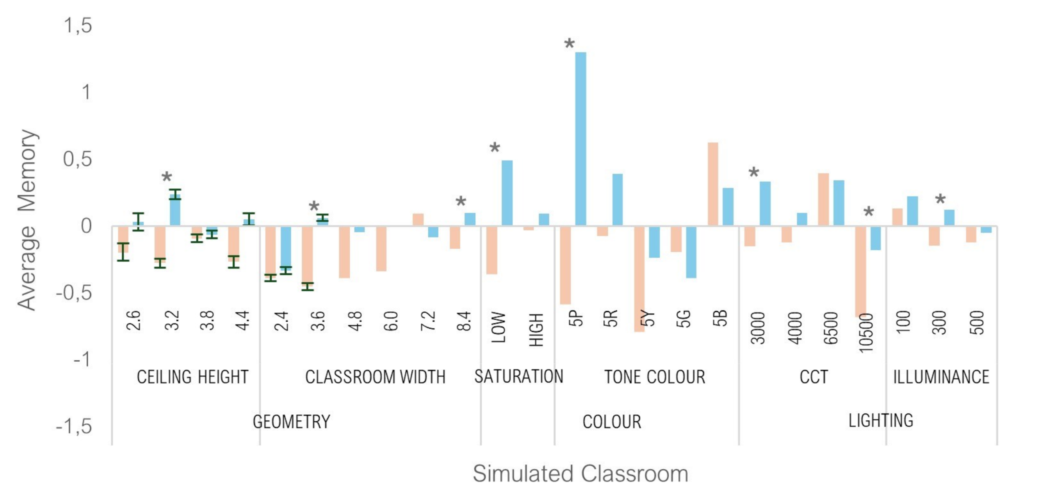
### *3.4. Phase IV. Comparative Analysis of the Effect of Classroom Design on Students' Memory as a Function of Gender*

Here, the differences in the analysed design configurations as a function of gender are analysed. Figure 21 shows the normalised means of both genders on the same graph.

Significant Differences by Gender for Changes in the Shape of the Classroom (Ceiling Height and Classroom Width). Although for either gender, the cei-



Figure 21. Normalised means of the psychological memory task. Memory-Correct Answers for men are shown in blue; and for women shown in orange. An asterisk marks the significant differences between genders.




ling height did not influence performance on the memory task, different results were nevertheless observed. In general, the results of males were higher than those of females for the different ceiling heights analysed. The ANOVA found significant differences in memory task performance for the height of 3.2 m ($p = 0.000$). Regarding the width of the classroom, it was observed that as the width of the classroom increased, better memory test results were produced in both groups. The change in trend in the results for men occurred from a width of 3.6m, whereas for women this change was observed from 7.2 m. It was this difference that produced significant differences for the width of 3.6 ($p = 0.037$).

Significant Differences by Gender for Changes in Classroom Colour (Hue and Saturation). Classroom colour saturation had a significant influence only for the women's group. However, a significantly different result ($p = 0.001$) was observed for both genders in the case of stimuli with low colour saturation. Thus, low saturation appeared to generate positive results in men and very negative results in women. With respect to hue, significantly different results were observed between males and females. The most pronounced difference was found in the 5P hue (purple) with a very positive result for men and a very negative result for women (p = 0.000). Significant differences were also detected in the 5Y (green) hue (p = 0.040).

Significant Differences by Gender for Changes in Classroom Lighting (Colour Temperature and Illuminance). The colour temperature of the lighting had a similar effect. Significant differences were detected at the extreme levels. In the case of the lowest colour temperature, 3000 K, memory test performance was above average for males and below average for females (p = 0.009). For the highest level of colour temperature, 10,500 K, a very negative performance was observed for both groups, but significantly lower for females (p = 0.000). In the case of illuminance, differences were observed at the 300 lx value, with above average performance for males and below average for females (p = 0.042).

## 4. Discussion

How the external context of a subject influences internal cognitive processes is a paradigm widely studied in the field of environmental psychology. Scientific analysis of aspects of spatial design in this field seeks to link two areas of knowledge that are apparently quite distinct: architecture, and educational psychology. Accepting the influence of external stimuli does not make the teacher's work less relevant, nor does it diminish examination of the students' internal perceptions. Rather, it serves to encourage a favourable outcome through the control of the physical variables of the given environment.

At a methodological level, the use of VR for spatial simulation should be highlighted, as it allows some variables under study to be easily modified while controlling others. In recent years, the use of VR in academic fields has become particularly relevant, with the year 2020 being a turning point on a global level due to the public health situation. Clearly, there are countless reasons for the use of



this new technology to be implemented in our societies, with specific VR design for activities to be developed from an evidential base. In this sense, studies that contribute to improving the design of these new learning environments are particularly relevant.

Regarding the results obtained, it is important to note that the cognitive performance of women in the memory test was generally lower than that of men. This phenomenon is possibly due to the task being carried out in a virtual environment. In this regard, Barrett and Lally (1999) showed that men and women play different social roles in the use of learning technologies. It has also been found that men have a greater preference for the use of multimedia technologies for learning due to a greater perceived usefulness of electronic devices (Park et al., 2019), familiarity with video games (Annetta et al., 2009; Rodríguez-Andrés et al., 2018), and a greater use of VR (Sánchez-Cabrero et al., 2019). There is also research conducted from virtual classrooms where differences are observed between men and women in terms of classroom design preferences (Cheryan et al., 2011).

Moreover, there is also evidence that learning differences between genders at school age are associated with task content (Kaushanskaya et al., 2013). Some authors conclude that gender difference could be correlated with the nature of spatial memory tasks (De Castell et al., 2019; León et al., 2014; Persson et al., 2013; Tascón et al., 2017) that relate to different forms of orientation and activation of brain structures (Fernández-Baizán et al., 2019; Grön et al., 2000; Persson et al., 2013). n tasks that involve technological elements, men show greater mental rotation than women (De Castell et al., 2019; Tascón et al., 2017). For this, men had greater activation of hippocampal structures while women of more cortical structures such as the frontal lobe (Grön et al., 2000). This may imply different ways of perceiving the virtual environment that act upon, albeit indirectly, the employment of memory.

When carrying out tasks in virtual environments, it is necessary to explore whether the differences obtained depend in a decisive way on the technology itself, on previous experience with the devices, or on the type of task set out. The specific results of classroom design do show that there are some elements of classroom design that influence both men and women in the same way, and others that differ in their influence according to gender. Knowing these differences makes it easier to suggest the creation of gender-equitable virtual environments.

Specifically speaking, ceiling height and illuminance do not influence memory performance. However, a small classroom width (2.4 m), and a high lighting colour temperature (10,500 K and above) have a negative impact on the memory task in both groups. However, the colour variable shows a large gender-related difference. Thus, women seem to be more sensitive to colour saturation as has been found in non-virtual (physical) environments (Yang & Jeon, 2020). It has been found that that low saturation used in the classroom generates negative results for women. The 5P (purple) hue has been identified as beneficial for males, but not for females. Based on this, the combination 5B (blue) and high saturation would be a good alternative for both genders, as it offers the best memory results for both groups without significant differences between them.

Finally, although the use of VR is a good tool to carry out this study, it cannot be used by students with glasses. This is a considerable limitation of the study. On the other hand, in terms of the limitations, it is important to take into account the possibility of synergistic effects between design elements not explored in this study. The "ceteris paribus" experimental logic applied in this study (which involves modifying each of the variables individually, keeping all other variables constant) gives rise to two issues: (1) there could be significant effects when combining the variables studied (geometry, colour, and lighting); and (2) other design variables to-date not analysed (for example, the position and design of the furniture or the virtual position of the participant in the classroom), by remaining the same in all experiences, could limit them to relatively similar situations.

## 5. Conclusions

This study analyses the influence of different physical aspects of a classroom on students' memory from a gender perspective. The results show relevant differences in the effects that design has on memory depending on gender, especially with purple wall colour and low saturation. This provides relevant information for the design of classrooms that benefit both groups.

Lighting, colour, and classroom dimensions are fundamental aspects to consider in the design of architectural teaching spaces, but they could also be of interest for the design of virtual learning environments that are increasingly present in our society. The use of VR in this study allows us to explore this. In educational settings, it has been suggested that it may offer even a better experimental context than physical settings (Parsons et al., 2007; Rizzo et al., 2000, 2009). In addition, this has allowed us to do something that was difficult until now: to study the influence of architectural elements on human behavior, overcoming the difficulties and cost of a real construction.

In this sense, the results may be of interest to design professionals or architects of classrooms in order to maximise the cognitive functions of students, regardless of gender. Research can also contribute to students' ability to shape space in virtual reality classrooms. However, it should not be forgotten that personal preferences of perception do not always coincide with a better level of memory. On the other hand, they may be relevant for teachers looking to adapt their teaching methodology given the existing physical characteristics of the classroom.

It would be interesting to analyse the joint effect of the combination of the studied variables and to see if these results are sustained in substantially different classroom typologies. Furthermore, future research may further address this question and whether gender differences are maintained over the years or whether, on the contrary, it is characteristic of youth and limited to learning contexts.

# Capítulo 6.

## Artículo del tercer estudio

El estudio recogido en este capítulo esta publicado como artículo de investigación, siendo su referencia bibliográfica la siguiente: Nolé, M. L., Soler, D., Higuera-Trujillo, J. L., & Llinares, C. (2022). Optimization of the Cognitive Processes in a Virtual Classroom: A Multi-objective Integer Linear Programming Approach. *Mathematics, 10*(7), 1184. https://doi.org/10.3390/math10071184

Dicho articulo aplica una aproximación matemática para el diseño del aula. En concreto, usa la programación lineal multiobjetivo para optimizar la memoria y atención de los estudiantes, así como su preferencia por el aula, a partir de la configuración de diferentes combinaciones de valores de diferentes parámetros de los elementos de diseño del propio aula.

La revista (ISSN 2227-7390) es de carácter internacional, transdisciplinaria, revisada por pares (siguiendo una single-blind review) y de acceso abierto. Proporciona un foro avanzado para estudios relacionados con las ciencias matemáticas. El special issue "Mathematical Models and Methods in Engineering and Social Sciences", en el que ha sido publicado el articulo, se centra en aplicaciones matemáticas en la investigación de las ciencias sociales y los factores humanos. En el año 2022 (anualidad de publicación del artículo), estaba indexada en los índices SJR (Q2 – FI: 0.446, 155/427, categoría "Engineering-miscellaneous") y JCR (Q1 –JCI: 2.08, 23/330, categoría "MATHEMATICS - SCIE"), medida de la calidad e influencia científica de las revistas académicas.

Abstract. A fundamental problem in the design of a classroom is to identify what characteristics it should have in order to optimize learning. This is a complex problem because learning is a construct related to several cognitive processes. The aim of this study is to maximize learning, represented by the processes of attention, memory, and preference, depending on six classroom parameters: height, width, color hue, color saturation, color temperature, and illuminance. Multi-objective integer linear programming with three objective functions and 56 binary variables was used to solve this optimization problem. Virtual reality tools were used to gather the data; novel software was used to create variations of virtual classrooms for a sample of 112 students. Using an interactive method, more than 4700 integer linear programming problems were optimally solved to obtain 13 efficient solutions to the multi-objective problem, which allowed the decision maker to analyze all the information and make a final choice. The results showed that achieving the best cognitive processing performance involves using different classroom configurations. The use of a multi-objective interactive approach is interesting because in human behavioral studies, it is important to consider the judgement of an expert in order to make decisions. Keywords: optimization; multiobjective integer linear programming; classroom design; cognitive learning processes.

## 1. Introduction

Multi-objective linear programming (MOLP) is a mathematical model in which two or more conflicting linear objective functions, which dependent on variables subject to certain linear constraints, are optimized simultaneously (Antunes et al., 2016; Herzel et al., 2020; Luptacik, 2010; Sakawa et al., 2013). MOLP has several variations; in particular, if all variables must be integers, the model is known as the multi-objective integer linear programming (MOILP), which will be the fundamental tool for the development of the study presented here.

Given the MOILP problem $Maximize\ \{Cx : Ax \geq b,\ x \geq 0\ and\ integer\}$, a feasible solution $x'$ is efficient if there is no other feasible solution $x$ such that $Cx' \leq Cx$ with at least one strict inequality. In this case, the objective vector $Cx'$ is called non-dominated. It is highly unlikely that a MOILP problem will have an optimal solution, and therefore, solving a MOILP problem generally entails identifying the set of its efficient solutions.

There are several algorithms to solve a MOILP problem. The very recent survey by Halffmann et al. (2022) presents all the exact algorithms known up to that date but also gives references on approximate algorithms. To solve a MOILP problem, scalarization methods, which, as their name indicates, turn such a problem into solving single-objective integer linear programming problems, play a crucial role in finding all or a subset of the non-dominated objective vectors. Note that a single-objective integer linear programming problem is known in the literature as an integer linear programming (ILP) problem (Chan et al., 2006; Fallah et al., 2023; Sherali & Driscoll, 2000; Tantawy, 2014; Tengan et al., 2018).

In this work, the scalarization known as the weighted sum is used (Alves & Clímaco, 2007). This basically consists of solving ILP problems where the objective functions are convex combinations of the objective functions in the original MOILP problem, with the same restrictions ($Ax \geq b, x \geq 0\ and\ integer$) plus $Cx \geq g$ where $g$ is a row vector of objective bounds. Each optimal solution to an ILP problem with the above conditions is an efficient solution to the MOILP problem.

Therefore, a method that generates the whole set, or a large subset, of non-dominated objective vectors may require an excessive amount of computational resources, which may make it inappropriate for dealing with large problems. Another approach is to use the so-called interactive methods (Antunes et al., 2016), which basically consist of phases of human intervention alternated with phases of computation. Human intervention is carried out by a decision maker (DM), which is a domain expert who can provide preferences toward solutions and select the most preferred one for implementation. It is essential that, on interactive methods, the computational effort is not too high in the computation phase and that the questions asked to the DM are simple and understandable. In these procedures, the DM makes the final choices.

In this work, an interactive method based on a MOILP weighted-sum scalarization is used to examine how classroom design affects cognitive processes. The objective of the study is to maximize learning (represented by memory, attention, and preference) from six classroom parameters (height, width, color hue, color saturation, color temperature, and illuminance).

MOLP has already been used to model problems in the field of human behavior, for instance, in psychology, for item calibration/selection in psychometrics (Köhn, 2011). Additionally,, very recently, González-Gallardo et al. (2021) used a variant of MOLP known as interval multi-objective linear programming (e.g., see Oliveira & Antunes, 2007) to analyze the well-being of students in Spain and Finland. Specifically, the main purpose was to study how four indicators (positive feelings, motivation, sense of belonging, and bullying) could be simultaneously improved while taking into account the particularities of both countries. This variation of the MOLP has also been used in order to simultaneously achieve a balanced performance in four measures of academic achievement from their use of the internet (Prieto-Latorre et al., 2021).

To solve the problem presented here, the help of virtual reality (VR) will be essential because VR allows researchers to overcome the difficulties, including cost, of using real spaces to study any one contextual key (keeping the others unchanged) in a controlled manner. VR can simulate different configurations of classroom characteristics. In recent years, VR has gained particular importance, with 2020 being the turning point at the international level due to the health situation. An increasing body of literature has validated the use of VR (Karakas & Yildiz, 2020; Marín-Morales et al., 2021) for perception studies (Ammann et al., 2020) and, specifically, environmental psychology studies (Armougum et al., 2019; Latini et al., 2021). Some authors (Díaz-Orueta et al., 2014; Iriarte et al., 2016; Rizzo et al., 2009) have concluded that VR is an efficient tool for measuring attention performance.

To collect the data, the subjects were presented with variations of a VR-based replica of a representative classroom at the Polytechnic University of Valencia. Six classroom parameters were varied: wall height and width, color hue, saturation and temperature, and lighting. Three objective functions were analyzed: memory, attention, and environmental preference. The solutions produced different cognitively efficient design configurations (in terms of memory and attention performance and environmental preference) that allowed the DM to analyze all the information and make a final choice. This is the fundamental contribution of this analytical methodology to the area of human behavioral studies, where statistical approaches have traditionally been applied. MOILP allows researchers to identify combinations of classroom design parameters that can simultaneously optimize cognitive processes taking into account the judgement of an expert.

The remainder of this work is organized as follows: Section 2 exhaustively reviews the existing literature about the influence of the environment on cognitive processes, including an analysis of how previous studies relate to this work. Section 3 explains the data collection process (procedure, conditions, software used for the VR, etc.). Section 4 presents the mathematical model, that is, the MOILP approach used to optimize the three functions cited above. Section 5 presents the results, which are discussed in Section 6, and finally, some conclusions and possible future research directions are provided in Section 7.

## 2. Related Cognitive Processing and Environment Works

Over the last decades, increasing attention has been paid to the influence of the environment on human beings at the cognitive–emotional level. Several studies have analyzed the effects of environmental characteristics on mental states and cognitive processes (Hoffman , 2020; Kim et al., 2020; Toews et al., 2020; Ulrich , 1984). Ulrich's (1984) pioneering study found that patients suffered less stress and enjoyed improved recovery in post-surgical scenarios when the windows of their rooms looked out onto natural vistas. Over the years, studies such as these have examined clinical populations and real environments and expanded into other contexts, such as education.

The study of the effects of classroom environments on experimental subjects must address two fundamental questions: first, how to assess improvements in learning, which can be understood as an active mental process of acquisition, retrieval, and use of information (Pritchard, 2017; Schunk, 2012), and second, which classroom characteristics influence this process?

Taking the first question, learning is a complex psychological construct. There is no consensus in the scientific community on its measurement: some studies focus on completing general tasks and others on specific tests of fundamental learning-related processes, such as attention and memory. Attention is a cognitive process that captures information from the environment (Brosowsky et al., 2021), and memory stores it (Jongbloed-Pereboom et al., 2015). The study of attention and memory involves performing specific tasks in specific environments. The nature of the tasks is important because it has been shown that the neuronal load involved in concentration prevents individuals becoming distracted (Sörqvis et al., 2015, 2016). Thus, easier tasks that require less concentration make people pay more attention to their environments. Another line of work, however, has examined subjects' preferences for environments. Perceptions of one's environment are important for two reasons: (1) There is a strong positive correlation between subjects' preferences and improvements in their mood (Gao et al., 2019); and (2) a brief, positive mood improvement enhances performance in short- and medium-term learning tasks (Bryan et al., 1996). That is, one's environment influences one's mood (Loewen & Suedfeld, , 1992), which, in turn, acts as a cognitive mediator, which results in positive perceptions, which strongly improve student performance (Aldridge & Rowley, 1998).

As to the second question, on classroom characteristics, it has been shown that when plants are present in the environment, student performance improves (Daly et al., 2010; Doxey et al., 2009; Van den Berg et al., 2017) and that the arrangement of furniture in classrooms influences teachers' behaviors (Wheldall et al., 1987), in-class teaching methodologies (Baum, 2018; Wannarka & Ruhl, 2008), and how students interact (Park & Choi, 2014; Shernoff et al., 2017; Wannarka & Ruhl, 2008). However, the central theme has been the influence of the built space on student learning. Thus, Marchand et al. (2014) recently discovered that in a space classified as uncomfortable (temperature of 26.67 °C, lighting of 2500 lx, and ambient sound of 60–65 dBA), university students scored lower in a reading comprehension test than students in a comfortable space (22 °C, 500 lx, 35 dBA); and it has been shown that a green-colored wall simulating vegetation did not improve subjects' performance in a specific test of sustained and selective attention in contrast to the effects of real vegetation found in a school classroom-based longitudinal study (Bernardo et al., 2021). However, most studies have analyzed the visual characteristics of classrooms.

The scientific literature highlights, among others, the visual characteristics of classroom color, lighting, and dimensions. These coincide with three of the seven characteristics of the built environment that have been shown to most influence the progress of primary school students (Barrett et al., 2015). As for color, it has been shown that in chromatic spaces, fewer errors are made in text correction tasks (Kwallek et al., 1996) and that tasks are performed quicker (Cockerill & Miller, 1983). It has also been shown that cold tones improve the performance of complex tasks (Stone, 2003; Xia et al., 2016) and enhance the cognitive processes, such as attention and memory, of university students (Llinares et al, 2021a). In addition, it has been shown that the contextual key of lighting influences student learning and performance (Jago & Tanner, 1999). For example, it has been observed that greater illuminance is associated with greater attention (Llinares et al., 2021c; Smolders & de Kort, 2014). In another line of work, Huiberts et al. (2015) observed that very bright, direct light improved the retrieval of numerical information in easy memory tasks, while more muted lighting was better when retrieving similar information in more difficult memory tasks. It has also been observed that higher color-temperature lighting (the light spectrum emitted by a black body heated to a certain temperature) produces faster cognitive processing speed and higher concentration (Keis, 2014) and better attention and memory task performance (Llinares et al., 2021c). As for dimensions, it has been observed that lower ceilings promote cooperation in school classrooms (Read et al., 1999) and that smaller classrooms are associated with better performance and higher arousal (Llinares et al., 2021b). In any case, while classroom dimensions have featured in many studies (Ahrentzen & Evans, 1984; Roskos & Neuman, 2021; Yang et al., 2013), they have not been their central focus; thus, there are few relevant conclusive results.

Although many studies have been undertaken in this area, they have all examined the individual characteristics of the classroom and cognitive processes in isolation, ignoring the impact they may have on each other. Classrooms have numerous characteristics, and it is possible that the results obtained from isolated analyses will differ from results obtained from combinations of characteristics. Thus, a good result in terms of lighting may be poorer when it is combined with a certain color or ceiling height, which might make subjects perceive the environment as a whole differently. The existing literature has not examined the effects of different combinations of classroom characteristics. In addition, researchers should simultaneously examine the different cognitive processes underlying learning, as some classroom characteristics might generate positive effects in one cognitive process and negative in others. Thus, for example, a study conducted with university students showed that low illuminance levels (100 lx–200 lx) improved memory but reduced attention (Llinares et al., 2021c; Smolders et al., 2012). An investigation into color showed that the subjects preferred blue and yellow tones, but these were associated with the poorest results in reading comprehension tasks (Al-Ayash, 2016). Thus, classroom designs must optimize the set of these cognitive processes.

Table 8 summarizes studies carried out into classrooms, detailing some relevant aspects.

The present study analyzes the simultaneous effects of different classroom characteristics on different cognitive processes. That is, an assessment is made of which design configurations of a university classroom (combining the characteristics lighting, color, and size) enhance the set of significant cognitive processes in learning, memory, attention, and preference). To do so, MOILP is used as an analytical tool and VR as an environmental-simulation tool.



Table 8. Summary of studies of human behavior in classrooms. [1]Heart rate variability. [2]Electroencephalogram. [3]Real classroom. [4]Experimental room.

| Reference | Classroom Design Parameters | Experience Register Behavioral | Experience Methods |
|---|---|---|---|
| Ahrentzen & Evans, 1984 | Interior Spaciousness; Degree of Open Perimeter and Amenities | Distraction; Privacy | RC [3] |
| Wheldall & Lam, 1987 | Seating Arrangements | Classroom Disruption Rate; Task Behavior; Teacher Behavior | RC [3] |
| Jago & Tanner, 1999 | Lighting; Color | Academic Progress | RC [3] |
| Read et al., 1999 | Ceiling Height; Wall Color | Cooperative Behavior | RC [3] |
| Wannarka Ruhl, 2008 | Seating Arrangements | Attention; Instructional Time | RC [3] |
| Doxey et al., 2009 | Plants | Cognitive Performance; Perception | RC [3] |
| Daly et al., 2010 | Plants | Classroom Performance | RC [3] |
| Yang et al., 2013 | Temperature; Air quality; Artificial and Natural Lighting; Acoustics; Visibility; Room Layout; Furniture; Hardware and Software. | Satisfaction; Performance | RC [3] |
| Park & Choi, 2014 | Seating Arrangements | Motivation; Participation | RC [3] |
| Marchand et al., 2014 | Lighting; Sound; Temperature | Student Learning; Mood; Environmental Perception | RC [3] |
| Smolders & de Kort, 2014 | Lighting (Bright Light) | Alertness; Vitality; Performance and Physiological Arousal (HRV [1] and Electrodermal Activity) | ER [4] |
| Keis et al., 2014 | Lighting (Blue-enriched White Light vs. Standard Lighting) | Speed of Cognitive Processing; Concentration Performance; Visuospatial and Verbal Memory | RC [3] |

| Reference | Classroom Design Parameters | Experience Register Behavioral | Experience Methods |
|---|---|---|---|
| Barrett et al., 2015 | Lighting; Temperature; Air quality; Ownership; Flexibility; Complexity; Color | Academic Progress | RC [3] |
| Huiberts et al., 2015 | Lighting (Illuminance Level and Bright Light) | Working Memory | ER [4] |
| Xia et al., 2016 | Color | Cognitive Task Performance | RC [3] |
| Al-Ayash et al., 2016 | Wall Color | Reading Task Performance; Emotional Responses; Neurophysiological (HRV [1]) | ER [4] |
| Van den Berg et al., 2017 | Green Walls vs. Plants | Cognitive Performance; Well-being | RC [3] |
| Shernoff et al., 2017 | Seating Location | Student Engagement; Attention | RC [3] |
| Baum, 2018 | Node Classroom vs. Spoke Classroom (Seating Arrangement; Lighting; Audio-visual and Computing equipment) | Classroom Activity; Student Attitude | RC [3] |
| Bernardo et al., 2021 | Plants | Sustained and Selective Attention; Working Memory | RC [3] |
| Llinares et al., 2021a | Wall color | Attention; Memory; Neurophy-siological (HRV [1] and EEG [2]) | VR |
| Llinares et al., 2021c | Lighting (Illuminance; CCT) | Attention; Memory | VR |
| Llinares et al., 2021b | Classroom Width | Attention; Memory; Neurophy-siological (HRV [1] and EEG [2]) | VR |



## 3. Materials and Methods

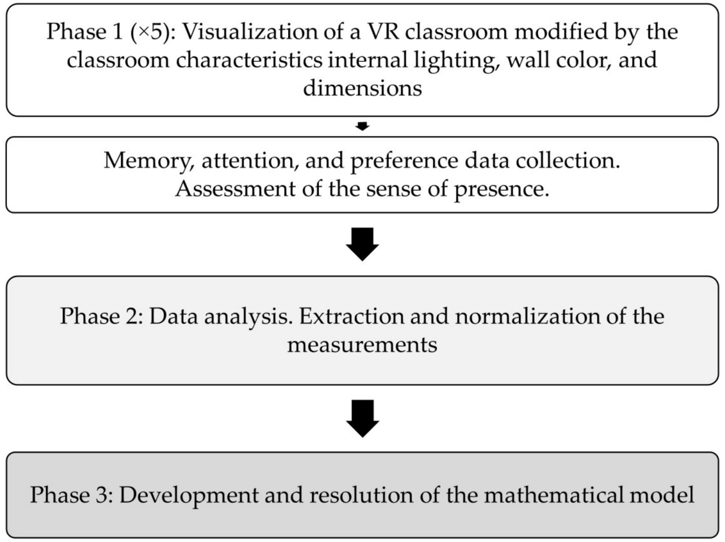
### *3.1. Participants*

The model used data collected from the Polytechnic University of Valencia student population. A total of 112 students participated (50.9% men, 49.1% women, mean age 23.24 years, standard deviation 3.79). To avoid the physical problems associated with VR glasses and to control cultural influences, the subjects were required to: (1) have good vision without glasses (they could wear contact lenses) and (2) be Spanish nationals. The procedure, including its non-invasive techniques, was explained to the participants, and they signed the appropriate informed consent form.

### *3.2. Procedure*

The study procedure is shown in Figure 22.

Figure 22. Schema of the study procedure.



In the first phase, a VR replica of a classroom at the Polytechnic University of Valencia was used as the base. Each participant viewed 5 randomly physically modified base classrooms. Each view was modified in the parameters of only one of the classroom characteristics: (a) wall color (hue and saturation); (b) interior lighting (illuminance and color temperature); and (c) dimensión (width and height of the walls). The levels of three psychological metrics and the students' sense of presence were assessed in this phase. Sense of presence is a crucial element of virtual environments. Presence can be understood as the user's illusion of "being there", in a virtual environment (Steuer, 1992), where (s) he has lost the sense of being in an environment simulated by a technological medium, and therefore, (s) he responds as if (s) he was in the real world (Lombard & Ditton, 1997). It has been found that sense of presence is directly related to the validity of the virtual experience (Higuera-Trujillo et al., 2017), understood as the similarity of the simulated experience to one generated by the physical environment represented. For this reason, sense of presence is sometimes used to validate virtual experiences. A detailed description of how the data were obtained is provided in the following two subsections.

### *3.3. Experimental Design*

The same experimental procedure was followed for all conditions, with only one difference, namely the type of classroom each subject viewed in the VR scenario: the base classroom was modified in color, lighting, and dimension. The criteria and processes associated with manipulating these three characteristics are described below.

#### Conditions

The original characteristics of the real classroom were maintained in each virtual reality scenario, modifications being made on an individual basis only to the parameters of the classroom characteristics. A set of specific values was selected from among the possible values of the different parameters. The criteria for choosing the color, illumination, and dimensions' values were based on the equitable distribution of colors in the Itten chromatic circle (Itten, 1987), on the information provided by the light bulb suppliers, and on the standard measurements used in the construction of removable ceilings.

A total of 29 values for the classroom parameters were obtained: 10 for color hue, 2 for color saturation, 3 for lighting, 4 for color temperature, 4 for height, and 6 for width. These were used to assess which combination optimizes memory, attention, and preference. It was not feasible for the experimental procedure to examine the 5760 ($10 \times 2 \times 3 \times 4 \times 4 \times 6$) possible combinations individually. It should be taken into account that each visualization and corresponding data collection took at least 30 min, and each had to be viewed by at least 5 subjects so that the data were statistically validated. Therefore, a comprehensive analysis would take more than 14,400 working hours.

Therefore, the study was simplified by using 56 variables. The variables examined were those resulting from combinations of the two parameters that made up each contextual key. Each variable corresponds to a modification of the base classroom. Thus, each modification involved changing the values of the two parameters that made up the classroom characteristics color, lighting, and dimensions. The changes were applied separately to the two parameters of the classroom characteristics, while the remaining parameters maintained their original values.

#### Materials Set-Up

The VR classrooms were recreated using Rhinoceros Software v.5.0 and the Corona Renderer Software v.2.0 These provided high-quality modeling and rendering, respectively. ColorMunki TM software was used to translate the 10 colors studied in Munsell notation into RGB notation.

The subjects viewed the classroom simulation, which allowed them to make changes to their visual fields through head movements through a head-mounted device (HTC Vive) connected to the researcher's computer. Unity3D was used to generate the software, which allowed the researcher to show the subjects the different scenarios through the HTC Vive.

The entire experiment was carried out in the same laboratory. The participants undertook the experiment in the same time slots, and the temperature (22.5 –23 °C) and sound insulation (34 dbA) were kept constant. The researcher's table and the participant's table faced each other in the center of the room.

### *3.4. Metrics*

Data on memory, attention, and preference were collected for each visualization. All were statistically normalized. The data collection is now described.

#### Memory Task.

The memory task was based on the auditory presentation of three out of a total of 16 randomized word lists. The lists were composed of 15 words in the same semantic field. Before the tests, the researcher said: "…then, you will hear a list of words. Try to remember them. Then, you will be asked to repeat them regardless of their order in a time of 30 s. This will be repeated 3 times." Thus, immediately after listening to the words, the subjects were asked to repeat those they could remember. Memory was measured by adding the number of words the subjects repeated from the 45 presented; thus, the more words remembered, the better the result. This is similar to the DRM experimental paradigm (Beato & Díez, 2001). The information was collected through audio recordings, which the researcher played back to calculate the number of correct words recalled by the participants.

#### Attention Task.

The attention task was based on the presentation of 3 lists of 40 sounds of 4 different types; 3 were distracting, and only 1 was objective. The subjects had 750 ms after the presentation of each sound during which to make a mouse click only to the target stimuli. Before the tests the researcher said: "…then, you will hear a series of sounds. You should react as soon as possible to this stimulus (target) by making a single mouse click and avoid clicking when you hear other sounds" (the 3 distractors). Attention was measured by calculating the average of the reaction times to the objective stimuli; thus, shorter times represented better results. This is similar to Seidman's (1998) continuous auditory performance test.



The information on reaction times was collected through software developed specifically for this research.

#### Preference Task.

The subjects' subjective perceptions of the environments were assessed through the degree of "I like" that they reported about their experiences of the classroom in a post-experiment written survey. This was rated through a Likert scale, from -4 to 4, addressed by the subjects at the end of their visualizations. The precise question was "Please rate your degree of agreement/disagreement with the following sentence (-4 being a high degree of disagreement, and +4 a high degree of agreement): In general, how much do you like this place?" To avoid any bias, the subjects were first told that there were no correct or incorrect answers. The question is based on that used by Galindo and Corraliza (2012) to assess general preference judgements in the Spanish population. The participants gave oral answers to the survey to the interviewers, who incorporated them into a database.

#### Sense of Presence.

The SUS questionnaire (Slater et al., 1994) was used to quantify sense of presence. This is a six-item self-report, rated from 1 to 7 on a Likert-type scale. The participants completed the questionnaire at the end of each classroom-simulation experience. The scenarios all achieved reasonably high mean values (mean = 29.38, standard deviation = 8.48). Based on the evidence provided by previous studies into presence (Slater & Steed, 2000), it can be concluded that the classroom simulations were satisfactory and that the results obtained are similar to those that might have been obtained by modifying actual classrooms.

### *3.5. Data Collection Results*

The objective of the problem is to maximize learning from classroom design features. Learning was represented by attention $(a)$ and memory $(m)$, cognitive processes directly related to learning, and preference $(p)$, which has an indirect effect. The design features were illumination $(x)$, dimension $(y)$, and color $(z)$, each of which is represented by two design parameters ($ij$): illuminance and color temperature for $x$, height and width for $y$, and hue color and saturation color for $z$. In the experimental process, these design features ($x_{ij}$, $y_{ij}$, and $z_{ij}$) were viewed by 10 participants, from whom $a$, $m$, and $p$ were collected. These data were normalized, subsequently obtaining the mean values by SPSS v. 26 software. These mean values represent the levels of $a$, $m$, and $p$ for the study population in each of the design situations. The points below provide a good understanding of the data and the formulae used in this work:

1. Let $a^x{}_{ij}$, $a^y{}_{ij}$, and $a^z{}_{ij}$ be the means of the levels of attention obtained in the lighting, dimension, and color conditions of the base classroom, respectively, for each combination. These values are shown in column 5 in Tables 9–11, which shows the sets where $i$ and $j$ vary in each case.
2. Let $m^x{}_{ij}$, $m^y{}_{ij}$, and $m^z{}_{ij}$ be the means of the levels of memory obtained in the lighting, dimensions, and color conditions of the base classroom, respectively, for each combination. These values are shown in column 4 in Tables 9–11, with the same sets for $i$ and $j$ cited above.
3. Let $p^x{}_{ij}$, $p^y{}_{ij}$, and $p^z{}_{ij}$ be the means of the levels of preference obtained for the lighting, dimensions, and color conditions of the base classroom, respectively, for each combination. These values are shown in column 6 in Tables 9–11, with the same sets for $i$ and $j$ cited above.
4. Let $\bar{a}^x$, $\bar{a}^y$, $\bar{a}^z$, $\bar{m}^x$, $\bar{m}^y$, $\bar{m}^z$, $\bar{p}^x$, $\bar{p}^y$, and $\bar{p}^z$ be the means of the values $a^x{}_{ij}$, $a^y{}_{ij}$, $a^z{}_{ij}$, $m^x{}_{ij}$, $m^y{}_{ij}$, $m^z{}_{ij}$, $p^x{}_{ij}$, $p^y{}_{ij}$, and $p^z{}_{ij}$, respectively, with their respective variations being $i$ and $j$. These values are shown at the end of the respective columns in Tables 9–11.
5. Let $x_{ij}$, $y_{ij}$, and $z_{ij}$ be the 0–1 variables whose values of 1 indicate that the classroom has lighting with illuminance of type $i$, color temperature of type $j$, dimensions with height type $i$, and width type $j$, and walls colored with hue type i, and with saturation type $j$, respectively. Conversely, a 0 value indicates that the classroom does not have type $i$ lighting and $j$ -type color temperature, dimensions of height type $i$ and width type $j$, and walls colored with tone type $i$ and saturation of type $j$, respectively. These variables are shown in column 3 of Tables 9–11, respectively.



Tables 9–11 provide the data obtained on illumination, dimensions, and color, respectively.

Table 9. Grouping of variables for each parameter of the classroom lighting characteristic.

| Illuminance | Color Temperature | Variable | $m^x{}_{ij}$ | $a^x{}_{ij}$ | $p^x{}_{ij}$ |
|---|---|---|---|---|---|
| 500 lx | 10,500 K | $x_{11}$ | -0.3573 | 0.4647 | 0.7778 |
| | 6500 K | $x_{12}$ | 0.1104 | -0.2373 | 0.6154 |
| | 4000 K | $x_{13}$ | -0.0857 | 0.208 | 0.6429 |
| | 3000 K | $x_{14}$ | -0.1174 | 0.0887 | -0.3571 |
| 300 lx | 10,500 K | $x_{21}$ | -0.5019 | -0.1531 | 0.3333 |
| | 6500 K | $x_{22}$ | 0.4349 | -0.7734 | 0.0714 |
| | 4000 K | $x_{23}$ | -0.0525 | 0.0225 | 0.011 |
| | 3000 K | $x_{23}$ | 0.2053 | -0.2405 | 0.4615 |
| 100 lx | 10,500 K | $x_{31}$ | -0.1168 | 0.0298 | 0.5714 |
| | 6500 K | $x_{32}$ | 0.5459 | -0.2542 | 1.3846 |
| | 4000 K | $x_{33}$ | 0.4598 | 0.1283 | 1 |
| | 3000 K | $x_{34}$ | -0.1188 | 0.2714 | 0.7059 |
| | | | $\bar{m}^x$= 0.0338 | $\bar{a}^x$= -0.0371 | $\bar{p}^x$= 0.5182 |

Table 10. Grouping of variables for each parameter of the classroom characteristic dimensions.

| Height | Width | Variable | $m^{y}_{ij}$ | $a^{y}_{ij}$ | $p^{y}_{ij}$ |
|---|---|---|---|---|---|
| 3.2 m | 8.4 m | $y_{11}$ | 0.2123 | -0.4279 | 1 |
| | 7.2 m | $y_{12}$ | 0.964 | 0.0556 | 0.1333 |
| | 6 m | $y_{13}$ | 0.3807 | -0.1804 | 1.1429 |
| | 4.8 m | $y_{14}$ | -0.3999 | 0.2504 | -0.625 |
| | 3.6 m | $y_{15}$ | -0.1748 | 0.4341 | -2 |
| | 2.4 m | $y_{16}$ | -0.6995 | 0.6277 | 0 |
| 3.8 m | 8.4 m | $y_{21}$ | -0.0828 | 0.1032 | -0.0814 |
| | 7.2 m | $y_{22}$ | 0.1614 | -0.0116 | 0.1333 |
| | 6 m | $y_{23}$ | -0.3945 | 0.5679 | 0.3333 |
| | 4.8 m | $y_{24}$ | 0.0007 | 0.5091 | -0.375 |
| | 3.6 m | $y_{25}$ | -0.4977 | -0.5824 | 0 |
| | 2.4 m | $y_{26}$ | -0.0565 | -0.1736 | -2.1667 |
| 4.4 m | 8.4 m | $y_{31}$ | 0.1639 | -0.6203 | 1.1429 |
| | 7.2 m | $y_{32}$ | 0.0575 | -0.27 | -0.1 |
| | 6 m | $y_{33}$ | -0.5299 | 0.0587 | -1 |
| | 4.8 m | $y_{34}$ | 0.0537 | 0.1453 | -0.1429 |
| | 3.6 m | $y_{35}$ | -0.1942 | -0.2556 | -1.3333 |
| | 2.4 m | $y_{36}$ | -0.5925 | 0.916 | -0.8333 |
| 2.6 m | 8.4 m | $y_{41}$ | -032256 | -0.432 | 0.5455 |
| | 7.2 m | $y_{42}$ | -0.1003 | -0.2714 | 0.3077 |
| | 6 m | $y_{43}$ | -0.1668 | 2.2663 | -1.2857 |
| | 4.8 m | $y_{44}$ | -0.2615 | 0.117 | 1 |
| | 3.6 m | $y_{45}$ | 0.1623 | -0.0309 | -2.625 |
| | 2.4 m | $y_{46}$ | 0.0421 | 0.7354 | -1.7143 |
| | | | $\bar{m}^{y}$= 0.0338 | $\bar{a}^{y}$= -0.0371 | $\bar{p}^{y}$= 0.5182 |



Table 11. Grouping of variables for each parameter of the classroom characteristic color.

| Height | Saturation | Variable | $m^{z}_{ij}$ | $a^{z}_{ij}$ | $p^{z}_{ij}$ |
|---|---|---|---|---|---|
| 5B | High | $z_{11}$ | 0.9211 | 0.0702 | -0.3333 |
| | Low | $z_{12}$ | -0.0039 | 0.2269 | -0.1667 |
| 5G | High | $z_{21}$ | -0.4155 | 0.2138 | □0.2 |
| | Low | $z_{22}$ | -0.2939 | 0.4916 | -2.1429 |
| 5GY | High | $z_{31}$ | -0.0421 | -0.0328 | -0.8333 |
| | Low | $z_{32}$ | -0.0758 | 0.3397 | 1.4286 |
| 5Y | High | $z_{41}$ | -0.6764 | -0.3718 | 1.1429 |
| | Low | $z_{42}$ | -0.1845 | -0.6578 | 1.8571 |
| 5YR | High | $z_{51}$ | 0.0605 | -0.1496 | 0.5 |
| | Low | $z_{52}$ | 0.0816 | -0.3638 | -0.3333 |
| 5R | High | $z_{61}$ | -0.1929 | 0.3043 | -2.125 |
| | Low | $z_{62}$ | -0.309 | 0.2662 | 1.5 |
| 5RP | High | $z_{71}$ | -0.2257 | 0.6897 | -0.625 |
| | Low | $z_{72}$ | -0.544 | -0.3037 | -2.1429 |
| 5P | High | $z_{81}$ | 0.3314 | 0.0233 | -1.1667 |
| | Low | $z_{82}$ | 0.9799 | -0.127 | -0.8333 |
| 5PB | High | $z_{91}$ | -0.1766 | -0.3066 | 0.2222 |
| | Low | $z_{92}$ | 0.249 | -0.073 | 1.5714 |
| 5GB | High | $z_{101}$ | -0.1321 | -0.0261 | 0.6667 |
| | Low | $z_{102}$ | 0.0734 | 0.0751 | -0.1429 |
| | | | $\bar{m}^{z}$= -0.0288 | $\bar{a}^{z}$= 0.0144 | $\bar{p}^{z}$= -0.1078 |

## 4. Mathematical Model

The problem of identifying the combinations of the six classroom parameters (height, width, color hue, color saturation, color temperature, and lighting) that provide the best results for memory and attention performance and preference was addressed by modeling a MOILP problem designed to optimize these functions. It should be noted that the aim is to maximize the memory and preference values and minimize the attention values.

Therefore, equality $Maximize\ f(x) = -Minimize\ (-f(x))$ is used for the attention function. With this equation, all the functions can be maximized.

Taking into account the information given in Section 3.3.1, the ideal MOILP problem should consider 5760 binary variables, each one corresponding to a different combination of color hue, color saturation, lighting, color temperature, height, and width. Its aim should be maximizing the three-dimensional vector corresponding to the average (normalized) results of memory, attention, and preference obtained for each one of the 5760 combinations. However, to pose and solve this problem is practically impossible due to the data collection time (more than 14,400 h) and to the number of variables. Instead, a more realistic situation is to consider the 56 variables introduced in Section 3.3.1 and detailed in Section 3.5 so that the three-dimensional vector to maximize has as components the sum of the means of the results of memory, the sum of the means of the results of attention, and the sum of the means of the results of preference (always normalized values) for each one of the 12 combinations of lighting and color temperature, 24 combinations of height and width, and 20 combinations of color hue and color saturation (a total of 56 combinations).

Therefore, using the notation given in Section 3.5, the following MOILP problem was formulated:



$$Maximize\left(\sum_{i=1}^{3}\sum_{j=1}^{4} m_{i,j}^{x}\cdot x_{i,j} + \sum_{i=1}^{4}\sum_{j=1}^{6} m_{i,j}^{y}\cdot y_{i,j} + \sum_{i=1}^{10}\sum_{j=1}^{2} m_{i,j}^{z}\cdot z_{i,j}\,,\right.$$
$$-\sum_{i=1}^{3}\sum_{j=1}^{4} a_{i,j}^{x}\cdot x_{i,j} - \sum_{i=1}^{4}\sum_{j=1}^{6} a_{i,j}^{y}\cdot y_{i,j} - \sum_{i=1}^{10}\sum_{j=1}^{2} a_{i,j}^{z}\cdot z_{i,j}\,, \qquad (1)$$
$$\left.\sum_{i=1}^{3}\sum_{j=1}^{4} p_{i,j}^{x}\cdot x_{i,j} + \sum_{i=1}^{4}\sum_{j=1}^{6} p_{i,j}^{y} y_{i,j} + \sum_{i=1}^{10}\sum_{j=1}^{2} p_{i,j}^{z}\cdot z_{i,j}\right)$$

*s.t:*

$$\sum_{i=1}^{3}\sum_{j=1}^{4} x_{i,j} = 1 \qquad (2)$$

$$\sum_{i=1}^{4}\sum_{j=1}^{6} y_{i,j} = 1 \qquad (3)$$

$$\sum_{i=1}^{10}\sum_{j=1}^{2} z_{i,j} = 1 \qquad (4)$$

$$\sum_{i=1}^{3}\sum_{j=1}^{4} m_{i,j}^{x}\cdot x_{i,j} + \sum_{i=1}^{4}\sum_{j=1}^{6} m_{i,j}^{y}\cdot y_{i,j} + \sum_{i=1}^{10}\sum_{j=1}^{2} m_{i,j}^{z}\cdot z_{i,j} \geq \bar{m}^{x} + \bar{m}^{y} + \bar{m}^{z} \qquad (5)$$

$$-\sum_{i=1}^{3}\sum_{j=1}^{4} a_{i,j}^{x}\cdot x_{i,j} - \sum_{i=1}^{4}\sum_{j=1}^{6} a_{i,j}^{y}\cdot y_{i,j} - \sum_{i=1}^{10}\sum_{j=1}^{2} a_{i,j}^{z}\cdot z_{i,j} \geq -\bar{a}^{x} - \bar{a}^{y} - \bar{a}^{z} \qquad (6)$$

$$\sum_{i=1}^{3}\sum_{j=1}^{4} p_{i,j}^{x}\cdot p_{i,j} + \sum_{i=1}^{4}\sum_{j=1}^{6} p_{i,j}^{y}\cdot y_{i,j} + \sum_{i=1}^{10}\sum_{j=1}^{2} p_{i,j}^{z}\cdot z_{i,j} \geq \bar{p}^{x} + p^{y} + \bar{p}^{z} \qquad (7)$$

$$x_{i,j}\,, y_{i,j}\,, z_{i,j} \in \{0,1\}\ \forall\ i,j \qquad (8)$$

Where:

Equation (1) represents the multi-objective function, that is, the vector with components students' memory, attention, and preference.

Equations (2)–(4) guarantee that each classroom is composed of a single parameter of illuminance and temperature in terms of lighting, height, and width (in terms of size) and a single parameter of hue and saturation (in terms of wall color), respectively.

Equations (5)–(7) ensure that the total memory value is higher than the sum of the memory means, the total attention value is higher than the sum of the attention means, and the total preference value is higher than the sum of the preference means, respectively. Note that these three inequations represent the logical lower bounds for the functions, and they can be changed for other more (or less) demanding inequations (Alves & Clímaco, 2007). The reason why these three restrictions were included in the formulation will be discussed later.

Equation (8) defines the problem variables as binaries.

Other linear restrictions could be added to the formulation if considered opportune. Moreover, it is obvious that this formulation can be extended to a more general formulation, with general bounds for i and j in each case, to more objective functions and to more variable types.

As stated in Section 1, there are several ways to obtain the set of efficient solutions to a MOILP problem. In this case, the following scalarization of the MOILP problem was used: Given $\lambda_1, \lambda_2, \lambda_3 \in \mathbb{R}^+$ with $\lambda_1 + \lambda_2 + \lambda_3 = 100$ and $b_m, b_a, b_p \in \mathbb{R}^+$ with $b_a \geq -\bar{a}^x - \bar{a}^y - \bar{a}^z, b_m \geq \bar{m}^x + \bar{m}^y + \bar{m}^z$ and $b_p \geq \bar{p}^x + p^y + \bar{p}^z$, the optimal solutions corresponding to each ILP problem formulated as follows are efficient solutions to the MOILP problem (Alves & Clímaco, 2007), with objective function given by Equation (9) and restrictions given by Equations (2)–(4), (8) and (10)–(12).



$$Maximize \quad \lambda_1\left(\sum_{i=1}^{3}\sum_{j=1}^{4} m_{i,j}^{x}\cdot x_{i,j} + \sum_{i=1}^{4}\sum_{j=1}^{6} m_{i,j}^{y}\cdot y_{i,j} + \sum_{i=1}^{10}\sum_{j=1}^{2} m_{i,j}^{z}\cdot z_{i,j}\right) + \lambda_2\left(-\sum_{i=1}^{3}\sum_{j=1}^{4} a_{i,j}^{x}\cdot x_{i,j} - \sum_{i=1}^{4}\sum_{j=1}^{6} a_{i,j}^{y}\cdot y_{i,j} - \sum_{i=1}^{10}\sum_{j=1}^{2} a_{i,j}^{z}\cdot z_{i,j}\right) + \lambda_3\left(\sum_{i=1}^{3}\sum_{j=1}^{4} p_{i,j}^{x}\cdot x_{i,j} + \sum_{i=1}^{4}\sum_{j=1}^{6} p_{i,j}^{y} y_{i,j} + \sum_{i=1}^{10}\sum_{j=1}^{2} p_{i,j}^{z}\cdot z_{i,j}\right) \quad (9)$$

$$\sum_{i=1}^{3}\sum_{j=1}^{4} m_{i,j}^{x}\cdot x_{i,j} + \sum_{i=1}^{4}\sum_{j=1}^{6} m_{i,j}^{y}\cdot y_{i,j} + \sum_{i=1}^{10}\sum_{j=1}^{2} m_{i,j}^{z}\cdot z_{i,j} \geq b_m \quad (10)$$

$$-\sum_{i=1}^{3}\sum_{j=1}^{4} a_{i,j}^{x}\cdot x_{i,j} - \sum_{i=1}^{4}\sum_{j=1}^{6} a_{i,j}^{y}\cdot y_{i,j} - \sum_{i=1}^{10}\sum_{j=1}^{2} a_{i,j}^{z}\cdot z_{i,j} \geq b_a \quad (11)$$

$$\sum_{i=1}^{3}\sum_{j=1}^{4} p_{i,j}^{x}\cdot x_{i,j} + \sum_{i=1}^{4}\sum_{j=1}^{6} p_{i,j}^{y}\cdot y_{i,j} + \sum_{i=1}^{10}\sum_{j=1}^{2} p_{i,j}^{z}\cdot z_{i,j} \geq b_l \quad (12)$$

Note that Equations (5)–(7) are particular cases of Equations (10)–(12), respectively. This is the fact by which they have been considered in the formulation of the problem. Therefore, from a theoretical point of view, solving a MOILP problem involves solving infinite ILP problems, as shown above (one for each combination of $\lambda_1, \lambda_2, \lambda_3, b_a, b_m,$ and $b_p$). However, it is likely that the vast majority of these ILP problems will have the same optimal solutions, and the total number of different efficient solutions will not be very high because the variables are integers and particularly in this case, where they are binary.

An interactive procedure based on the scalarization described above is used here to obtain good (according to the DM), efficient solutions to the MOILP problem. As usual with this method, a subset of efficient solutions is generated, and from this subset, the DM draws conclusions and proposes, for instance, new bounds for the objective functions to generate a new subset of efficient solutions, which are in turn analyzed by the DM and so on, until the DM decides which are the most efficient solutions to the MOILP.

The proposed heuristic is shown below. This procedure does not guarantee identification of the complete set of efficient solutions, but based on the problem's characteristics, it is expected that it will obtain a representative set of solutions.

Heuristic:

Step 1. For each combination of even numbers $\lambda_1, \lambda_2, \lambda_3 \in \mathbb{N}^+$ with $\lambda_1 + \lambda_2 + \lambda_3 = 100$ (1176 ILP combinations), solve (with Mathematica v12.1) the ILP problem with Equation (9) as the objective function, using the restrictions of Equations (2)–(8). Solve the same problem but with $\lambda_1 = \lambda_2 = \lambda_3 = 100/3$ (the same weight for all three objective functions). The DM assesses the set of optimal solutions obtained (all of them are efficient solutions to the MOILP problem) and makes decisions, such as removing from the list of solutions those not considered adequate, and establishes (increases or decreases) the percentile to be used in Step 2.

Step 2. Repeat Step 1, changing the right-hand side of Equations (5)–(7) by the percentile $i$ provided by the DM of the list of 1177 non-dominated objective vectors corresponding to each objective function (in the first execution of Step 1). The new solutions obtained are saved (although sometimes no solution is obtained). This step is repeated until no further solutions emerge, and all the percentiles $j$ with $j < i$ have been considered along the heuristic or until the DM decides that even if more solutions may exist, it is not important to identify them.

Step 3. The DM draws conclusions about those efficient solutions obtained in the process that remain in the list.

The criteria to be used by the DM to remove or maintain efficient solutions in the list in Step 2 and to decide which are the best solutions in Step 3 depend on the situation. Thus, in general, the classroom will be designed to take account of



all three cognitive processes (memory, attention, and preference), but it is possible that, in circumstances in which a high cognitive load is required, such as taking an exam, the DM will choose a criterion prioritizing memory and attention over preference.

To give a general idea of how the heuristic works, in Step 2, the lower bounds for the values of the objective functions vary; these variations are the percentiles of the 1177 initial solutions. The higher the percentile, the greater the requirement for the objective functions. If, for instance, the DM introduces a high percentile, and none of the 1177 ILP problems has a feasible solution, during the next Step 2 run, the DM might lower the percentile to try to obtain new solutions or even to terminate the process. The number of iterations will be finite, as it is obvious that from a certain percentile (unknown a priori), no new solutions will be found.

Note that, in each iteration, the proposed heuristic must optimally solve 1177 ILP problems, each of which theoretically has exponential complexity. Therefore, from a computational viewpoint, this is a complex heuristic; but the Mathematica V.12 tool has been shown to be very effective in this regard. This fact, together with the simplicity of the alternation and connection between the computation phases and the intervention phases of the DM, has prompted the authors of the present study to opt for this heuristic although, obviously, other procedures could have been applied to obtain a reasonable set of "good", efficient solutions to the MOILP problem here formulated.

## 5. Results

The results obtained by the heuristic are shown in Table 12. On the 1st run of Step 1, only 10 efficient solutions were obtained from the 1177 ILP problems. This caused the DM to adopt a conservative stance and advance from percentile to percentile. The DM decided not to discard any of the 10 solutions and to apply the 1st percentile in the 1st run of Step 2. On the 2nd run of Step 1, seven efficient solutions to the MOILP problem were obtained from the new 1177 ILP problems, only two of which were new. The DM decided not to discard any of the 12 solutions and applied the 2nd percentile in the 2nd run of Step 2. Only two efficient solutions were obtained during the 3rd run of Step 1 from the new 1177 ILP problems, only one of which differed from those previously obtained. The DM decided not to discard any of the 13 solutions and applied the 3rd percentile in the 3rd run of Step 2. None of the 1177 ILP problems assessed in the 4th run of Step 1 had a feasible solution; therefore, the heuristic procedure was terminated after the DM provided conclusions on the 13 efficient solutions obtained (provided below).

The Mathematica software was run on a PC Intel®CoreTM I5-7500 with 3.40 GHz and 16GB RAM. The average CPU time to obtain the optimal solution on all ILP problems was 0.0035 s, with a maximum value of 0.0156 s and a minimum value of 0 s, which, according to Mathematica's assumptions, means that the calculation took no measurable CPU time.

Figure 23 represents the position in three-dimensional space of the points corresponding to the 13 non-dominated objective vectors obtained by the heuristic. Note that the Mathematica software automatically scales the points. Figure 24 shows the points of the vectors of the three objective functions on the same scale. It is worth remembering that the values entered in Equation (1) are normalized.

In Step 3, the DM identified the four best solutions based on the different selection criteria. The first criterion is to ensure that the three objective functions are broadly in balance, that is, that one is not more salient than the others. Based on this decision, the DM chose solutions 9 and 10. It is worth mentioning that solution 10 attached equal importance to the three metrics ($\lambda_1 = \lambda_2 = \lambda_3 = 100/3$) and was the most frequently cited solution to the 1770 problems. Another possible criterion would be to prioritize memory and attention over preference, particularly relevant in the design of classrooms where important cognitive effort is required, such as for exams. In this case, the DM would select solutions 1 and 3. Table 13 lists the design configurations of these four solutions.



Table 12. Set of efficient solutions obtained with the heuristic. [1] n represents the frequency with which the solution was repeated among the 1177 possible. 2 r-h side column shows the right-hand side values of Equations (5)–(7).

| Solutions | $n$ [1] | Memory | Attention | Preference | R-h Side [2] | Step 1 |
|---|---|---|---|---|---|---|
| 1: $x_{22}=1, y_{13}=1, z_{82}=1$ | 9 | 1.7955 | 1.0808 | 0.381 | | |
| 2: $x_{22}=1, y_{31}=1, z_{42}=1$ | 200 | 0.4143 | 2.0515 | 3.0714 | | |
| 3: $x_{22}=1, y_{31}=1, z_{82}=1$ | 55 | 1.5787 | 1.5207 | 0.381 | | |
| 4: $x_{32}=1, y_{13}=1, z_{11}=1$ | 50 | 1.8477 | 0.3644 | 2.1942 | | |
| 5: $x_{32}=1, y_{13}=1, z_{42}=1$ | 108 | 0.7421 | 1.0924 | 4.3846 | $b_m$ = -0.1218; $b_a$ = -0.1244; $b_p$ = -.0686 | 1st run |
| 6: $x_{32}=1, y_{13}=1, z_{82}=1$ | 86 | 1.9065 | 0.5616 | 1.6942 | | |
| 7: $x_{32}=1, y_{13}=1, z_{92}=1$ | 121 | 1.1756 | 0.5076 | 4.0989 | | |
| 8: $x_{32}=1, y_{31}=1, z_{42}=1$ | 527 | 0.5253 | 1.5323 | 4.3846 | | |
| 9: $x_{32}=1, y_{31}=1, z_{82}=1$ | 18 | 1.6897 | 1.0015 | 1.6942 | | |
| 10: $x_{32}=1, y_{31}=1, z_{92}=1$ | 3 | 0.9588 | 0.9475 | 4.0989 | | |
| 11: $x_{22}=1, y_{31}=1, z_{92}=1$ | 16 | 0.6593 | 1.5433 | 1.7143 | | |
| 12: $x_{22}=1, y_{31}=1, z_{82}=1$ | 131 | 0.8478 | 1.4667 | 2.7857 | | |
| 5: $x_{32}=1, y_{13}=1, z_{42}=1$ | 672 | 0.7421 | 1.0924 | 4.3846 | | |
| 6: $x_{32}=1, y_{13}=1, z_{82}=1$ | 140 | 1.9065 | 0.5616 | 1.6942 | $b_m$ = 0.4143; $b_a$ = 0.5076; $b_p$ = 1.6942 | 2nd run |
| 7: $x_{32}=1, y_{13}=1, z_{92}=1$ | 127 | 1.1756 | 0.5076 | 4.0989 | | |
| 8: $x_{32}=1, y_{31}=1, z_{42}=1$ | 83 | 1.6897 | 1.0015 | 1.6942 | | |
| 9: $x_{32}=1, y_{31}=1, z_{82}=1$ | 8 | 0.9588 | 0.9475 | 4.0989 | | |
| 10: $x_{32}=1, y_{31}=1, z_{92}=1$ | 1124 | 0.9588 | 0.9475 | 4.0989 | $b_m$ = 0.5253; $b_a$ = 0.5616; $b_p$ = 3.0714 | 3rd run |
| 13: $x_{32}=1, y_{11}=1, z_{92}=1$ | 53 | 1.0072 | 0.7551 | 3.956 | | |

Figure 23. Three-dimensional graph of the efficient solution set.

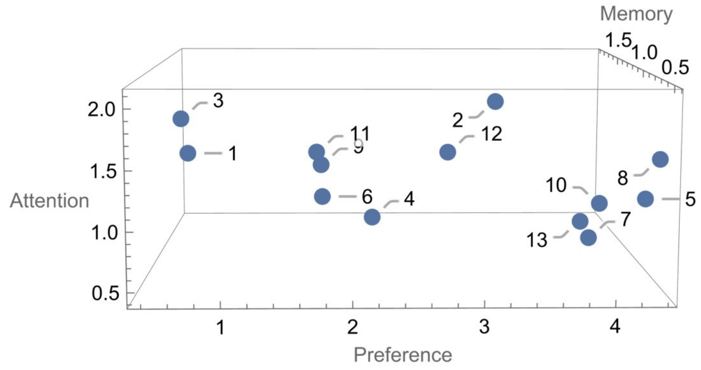



Figure 24. Levels of psychological metrics of each efficient solution.

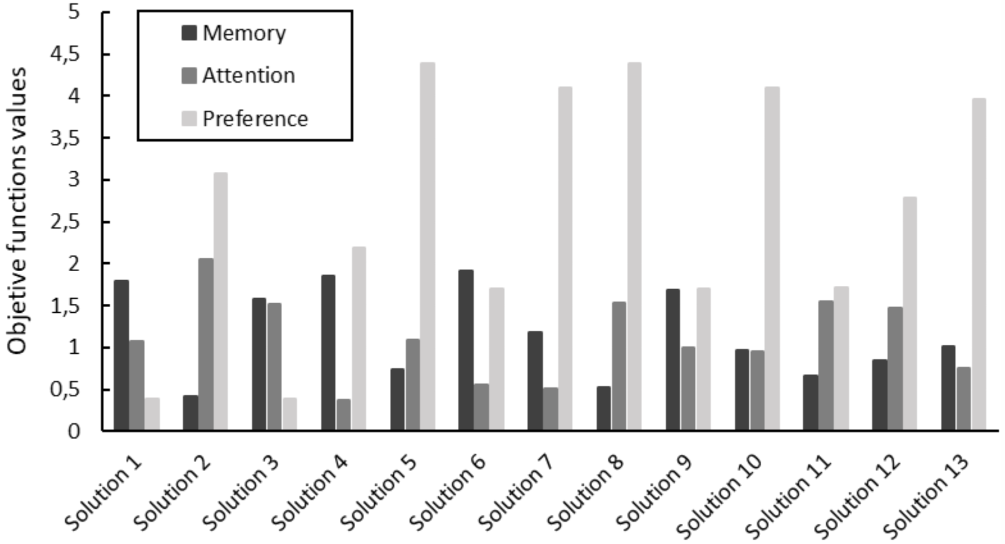





Table 13. Design configurations for the best solutions.

| Design Parameters | | Decision Criterion: Better (Memory, Attention, Preference) 10 | 9 | Better (Memory, Attention) 1 | 3 |
|---|---|---|---|---|---|
| Lighting | Color Temperature | 6500 K | 6500 K | 6500 K | 6500 K |
| | Illuminance | 100 lx | 100 lx | 300 lx | 300 lx |
| Color | Hue | 5PB | 5P | 5P | 5P |
| | Saturation | low | low | low | low |
| Dimension | Height | 4.4 m | 4.4 m | 3.2 m | 4.4 m |
| | Width | 8.4 m | 8.4 m | 6 m | 8.4 m |

As shown in Table 13, the best solutions have the same illumination color temperature (6500 K) and the same wall color saturation (low). The difference between the solutions, according to the decision criteria, is in illuminance. A higher illuminance level (300 lx) enhances attention and memory processes although it is regarded as less pleasant, decreasing preference level. The solutions with the best results in attention, memory, and preference levels (9 and 10) have the same characteristics in terms of lighting, color saturation, and dimension but feature different hues. On the other hand, the solutions that enhance attention and memory feature the same configurations except in dimensions.

## 6. Discussion

The present study aims to identify the combination of classroom design parameters that optimize students' internal psychological processes by applying MOLP as an analysis method and using VR as an environmental-simulation tool. The study makes three fundamental contributions: one methodological, one at the results level, and one at the application level.

As for the methodological contribution, a mathematical analysis was undertaken to complement the traditional statistical approach of the behavioral study. In this sense, this methodology is novel and ideal for: (1) identifying the design configurations that take into account the combination of parameters that make up spaces, as in real scenarios; (2) optimizing several objective psychological metrics, which is of special interest for multi-functional spaces; and (3) considering the judgement of an expert, which is important in human behavior studies.

The results of the present study provided a small set of efficient solutions to be evaluated by the DM. As shown in Table 12, there are two possible selection criteria. On the one hand, taking into account the three cognitive processes, the DM would select solutions 10 and 9, which combine dimensions of 4.4 m height and 8.4 m width, interior artificial lighting of 6500 K and 100 lx, and low-saturation blue or purple wall color. These solutions are suitable, as they maintain a high level of preference and the best combination of attention and memory levels. Moreover, solution 10 gives all three psychological metrics equal importance ($\lambda_1 = \lambda_2 = \lambda_3 = 100/3$). Another possible criterion would be to prioritize memory and attention over preference given their importance in learning (Pritchard, 2017; Schunk, 2012). Both are important for class sessions with activities that require different levels of cognitive load, such as taking exams (Vogel & Schwabe, 2016), undertaking projects (Sart, 2014), and teaching through alternative educational methodologies, such as the flipped classroom (Mattis, 2015). In this case, the DM would choose solutions 1 and 3, which combine interior artificial lighting of 6500 K and 300 lx, low-saturation purple wall color, and dimensions of 3.2 m height and 6 m width or 4.4 m height and 8.4 m width. These solutions, while subject to the constraints of the model, are efficient for this set of cognitive processes; while they present the lowest preference values, they achieved the highest values in the combination of attention and memory. The preference–performance relationship has been examined in many studies, but no conclusive results have been achieved. Some authors have negatively correlated the two (Al-Ayash et al., 2016), and others have done so positively (Burke & Burke-Samide, 2004).



In any case, this research provides concrete design results to consider. The benefit of using a color temperature of 6500 K was clear for attention, memory, and preference. In addition, some authors have observed that blue-enriched white light has a positive effect on performance (Keis et al., 2014; Ferlazzo et al., 2014). The combination of high lighting color temperature (6500 K) and low illuminance (100 lx and 300 lx) was common to all 13 solutions. Several authors have shown that lower illuminance improves cognitive performance (Leccese et al., 2020; Leichtfried et al., 2015). This lighting effect is repeated with color. Virtually all the solutions featured low-saturation colors. Similarly, Kwallek et al. (1996) observed that fewer errors were made in performance tasks in environments with colors of saturations similar to or lower than those used in the present study. The solutions included both cold and warm hues. On this issue, the literature is conflicting. Some authors, for example, Mahnke (1996), have argued that better academic performance is achieved with blue colors in high/secondary school classrooms, while Barret et al., (2013) observed that warm-hue colors are more appropriate for senior grades and that cold-hue colors are more appropriate for junior grades. As to the dimensions contextual key, in no case did lower ceilings (2.4 m) or narrow classrooms (3.6 m) improve student performance. Specifically, heights between 3.2 m and 4.4 m and widths between 6 m and 8.4 m provided efficient solutions. This outcome may be consistent with the results obtained by Vartanian et al. (2015), in which high ceilings were evaluated as more beautiful than low ceilings because they expanded the viewers' fields of view.

Regarding the application contribution, this article connects two different fields of study: architecture and psychology. In general, from the architectural perspective, studies have analyzed human responses to built spaces taking preference as the main decision-making criterion (Herzog, 1992; Stamps, 1993) and used psychological metrics other than task performance, that is, through self-reports (Yang et al, 2013;Lipczynska et al., 2018); this may be a limited approach. The present study proposes using environmental preferences (typical in architectural studies) and the results of tests analyzing cognitive processes (typical in psychology studies) to bridge the gap between the two disciplines.

## 7. Conclusions and Future Research

This study addresses the complexity of the analysis of the effects of classroom environments on subjects. This complexity drives the need to analyze the various environmental characteristics of classrooms and the cognitive processes involved in learning. This process requires the application of techniques that can simultaneously analyze a large number of variables. In the present study, the MOLP analysis technique was applied to optimize this set of variables. The advantages of this method for this work are: (1) it takes into account the interdependencies between classroom characteristics; (2) it maximizes the levels of the cognitive processes attention, memory, and preference; and (3) it provides several efficient solutions to allow the DM to select the most appropriate depending on the situation. In this case, the best solutions share interior artificial lighting of 6500 K and low-saturation wall colors. If the DM wants to achieve high levels in the three psychological metrics (memory, attention, and preference), the classroom should also be 4.4 m high and 8.4 m wide and have 100 lx of lighting and blue or purple wall color. If, on the other hand, the requirement is to enhance only the cognitive functions of attention and memory, the DM will choose a classroom combining 300 lx and low-saturation purple wall color, with dimensions of 3.2 m height and 6 m width or 4.4 m height and 8.4 m width. These results may be of interest to researchers and professionals involved in the design of educational centers.

Finally, as for future research lines, three aspects should be considered. First, the present study used auditory tasks to examine the processing of classroom characteristics. In future works, it would be interesting to include other types of tasks, as information processing through other sensory pathways requires different neural bases (Bear et al., 2016; Carlson, 2010; Barret et al., 2010). Second, regarding the stimuli presented, it would be interesting to address the influence of multisensory contextual cues (Yang & Moon, 2019). Synergies between interior design parameters may involve senses other than sight, such as auditory and tactile temperature receptors (Marchand et al., 2014). Third, regarding the sample, it would be interesting to analyze whether differences exist between men and women (Picucci et al., 2011; Miola et al., 2021). In all these lines, MOILP analyses with appropriate interactive methods can help researchers to obtain good results.

# Capítulo 7.

## Discusión general

Este capítulo presenta la discusión general que supone una interpretación del contenido global de esta memoria doctoral. Los dos primeros apartados profundizan en los resultados obtenidos en los capítulos cuatro a seis. Los dos apartados siguientes abordan la implicación del género y de la propia metodología empleada en los tres estudios que han sido desarrollados. Un último apartado aborda las limitaciones y futuras investigaciones.

### 1. Impacto de los diferentes elementos de diseño del aula en el alumnado

Las características físicas del ambiente educativo, como la luz, el color y la dimensión del aula, influyen en el aprendizaje y el bienestar de los estudiantes. El impacto de estos elementos se ha examinado de forma independiente en los tres subapartados siguientes. Cada uno de estos apartados tienen la misma estructura con dos abordajes principales: la influencia del elemento correspondiente en los tres procesos cognitivos (resultados obtenidos en el capítulo cuatro) y la influencia de cada uno de los parámetros del correspondiente elemento en la memoria del alumnado (resultados obtenidos en el capítulo cinco).

#### *1.1. Luz interior del aula.*

Del conjunto de intervenciones a llevarse a cabo en un aula, la luz (frente a las intervenciones en color o dimensión) es el elemento de diseño que más afecta a la cognición del alumnado. Los cambios de luz generan un efecto significativo en los tres procesos cognitivos estudiados:: preferencia del conjunto de los sujetos, en la memoria de los hombres y en la atención de las mujeres. Es decir, la luz parece ser el parámetro al cual los procesos cognitivos son más sensibles. La iluminación tiene una relación directa con la fisiología humana debido a que el ciclo de luz y oscuridad actúa como un regulador potente de nuestros ritmos de actividad (Tähkämö et al., 2019). Los cambios en la iluminación provocan alteraciones no conscientes en el rendimiento cognitivo, afectando a los niveles de alerta (Chellappa et al., 2011). Esta influencia justifica el impacto de las variaciones de la iluminación del aula en la memoria y la atención de los estudiantes. Además, las diferencias en la preferencia podrían explicarse considerando esta relación biológica junto con la teoría de la adaptación, que sugiere que la percepción de un estímulo está influenciada por factores contextuales y la experiencia previa del individuo (Helson, 1964). Ello es aplicable al marco de nuestro estudio, donde se realizó una valoración secuencial de espacios con variación en la iluminación del aula base.

Un posterior análisis de cada uno de los parámetros de luz (iluminancia: 100lx, 300lx y 500lx; CCT: 3000K, 4000K, 6500K y 10500K) profundizó en la afectación de la memoria de los estudiantes. Así, un valor de 6500K genera los mejores niveles de memoria para ambos géneros, sin observar diferencias significativas entre ellos. Se ha demostrado que la concentración de los estudiantes y el rendimiento en un entorno de oficina mejora en presencia de una iluminación con CCT entre 5500- 6500K frente a 3000-3500K, respectivamente (Bao et a., 2021; Keis et al., 2014). Por su parte, Llinares y colaboradores (2021c) encontraron resultados similares con un mejor rendimiento de la memoria con una iluminación de 100lx

### *1.2. Color de las paredes del aula.*

Las intervenciones del color (tono y saturación) de las paredes de un aula deben contemplarse como la segunda ejecución de más relevancia para la modificación de un aula. Esta afirmación se fundamenta en que los cambios de color,



con respecto al aula base de paredes blancas, repercute al nivel de atención del conjunto de alumnos, con especial incidencia en las mujeres. Este resultado es coherente con investigaciones previas que demostraron diferencias en el rendimiento de los trabajadores en espacios de oficina con diferentes colores frente a oficinas de color blanco (Kwallek et al., 1996).

Un estudio más exhaustivo de la incidencia de cada parámetro de diseño (saturación: alta y baja; tono: azul, verde, morado, anaranjado y amarillo) en la memoria arrojó resultados relevantes. La saturación alta genera un mejor rendimiento en las pruebas de memoria, siendo muy significativa esta mejoría para las mujeres. Con respecto al tono, los mejores resultados se obtuvieron con colores fríos (morado para los hombres y azul para las mujeres). Un diseño más inclusivo requeriría el uso del azul, ya que el morado generaba desigualdades en el rendimiento entre ambos géneros. Además, de los resultados se desprende que sería recomendable evitar el color amarillo y el verde, ya que repercuten negativamente en la memoria de ambos géneros y de los hombres, respectivamente. Es importante señalar que la literatura científica aún no aborda ampliamente la relación entre la saturación del color de las paredes y la memoria, de forma que no existen conclusiones definitivas al respecto. Por su parte, estudios previos han destacado los beneficios de los tonos fríos en el rendimiento cognitivo, a diferencia de los tonos cálidos, con impacto negativo (Llinares et al., 2021a). En otro contexto, se ha observado que la visualización de colores cálidos como el rojo repercute negativamente en el desempeño cognitivo (Elliot & Maier, 2007).

### *1.3. Dimensión del aula*

De las posibles intervenciones de luz, color y dimensión de un aula, este último elemento es el que tiene menor efecto en la cognición del estudiante. Las modificaciones de la dimensión (alto de techos y ancho del aula) solo afecta a los niveles de atención, sin mostrar una especial afectación a ningún género. Por lo tanto, este elemento de diseño es el que menos influencia tiene y, además, es el que supone un coste más importante para su intervención. Según la teoría de la carga cognitiva, la capacidad de atención de una persona es limitada y puede verse influenciada por la cantidad de estímulos o información presentes en un espacio de determinado tamaño (Sweller, 2011). Siguiendo esta línea, Blatchford y colaboradores (2003) han demostrado que las clases más grandes, distraen más al alumnado. A pesar de esta influencia en la atención, la dimensión es el elemento menos influyente en la cognición del alumnado.

Un segundo análisis, centrado en la dimensión, comparó el efecto de diferentes parámetros de altura (2.6m, 3.2m, 3.8m y 4.4m) y anchura (2.4m, 3.6m, 4.8m, 6m, 7.2m, 8.4m) sobre la memoria, arrojando resultados relevantes. Así, se observó que a medida que aumenta la anchura del aula mejoran los resultados de la prueba de memoria, siendo las dos aulas más anchas las que favorecieron de forma significativa la memoria del conjunto de los sujetos. No obstante, de estas dos medidas un diseño más inclusivo requeriría un ancho de 7.2m, puesto que 8.4m genera desigualdades en el rendimiento de memoria entre hombres y mujeres. Esto es coherente con que, en términos generales, las personas tienen preferencia por espacios más amplios (Hur et al., 2010). Además, en un contexto diferente al de las aulas, otros estudios han observado que los espacios interiores amplios consiguen generar una mayor activación de diferentes zonas cerebrales, como la corteza cingulada (Vartanian et al., 2015), estrechamente relacionada con el sistema de memoria del hipocampo (Rolls, 2019). Estos resultados, sin embargo, deben interpretarse con cautela, dado que el contexto utilizado difiere del de las aulas y la observación del espacio no implicaba ninguna tarea específica, sino una visualización pasiva del mismo. ´

## 2. Impacto del efecto combinado de los diferentes elementos y parámetros de diseño del aula en el alumnado

Los resultados obtenidos en el capítulo seis sobre el estudio de la combinación de los parámetros de cada elemento de diseño difieren, en cierta medida, de los resultados obtenidos en el análisis individual de cada uno de ellos. Esto sugiere que la interacción entre los parámetros de diseño es crucial para comprender su impacto en el usuario.



En este contexto, un enfoque matemático propone un conjunto específico de En este contexto, el enfoque matemático empleado propone un conjunto específico de combinaciones óptimas que los diseñadores, como expertos, deben considerar al planificar entornos educativos. Se identificaron dos combinaciones particulares que destacan por su capacidad para mejorar tanto la memoria como la atención de los alumnos: una iluminación de 6500K y 300lx, con un color morado de baja saturación, y dimensiones físicas específicas (alturas de 3.2m o 4.4 m y anchos de 6m o 8.4 m, respectivamente). Estas configuraciones priorizan la memoria y la atención debido a su importancia en el proceso de aprendizaje. Por otro lado, para optimizar de manera integral la experiencia del usuario en el entorno educativo, se identificaron otras dos combinaciones alternativas que equilibraban la importancia de todas las métricas psicológicas (incluida la preferencia): una iluminación de 6500K y 100lx, con un color morado o azul, y las mismas dimensiones físicas mencionadas anteriormente.

En las combinaciones resultantes se evidencia la utilidad de emplear una temperatura de color intermedia de 6500K y una iluminancia baja o intermedia de 100/300lx para mejorar la atención, la memoria y la preferencia en entornos educativos. Este enfoque se alinea con investigaciones previas que han destacado el efecto positivo de una iluminación reducida en el rendimiento cognitivo (Leccese et al., 2020; Leichtfried et al., 2015). En relación con los resultados de color, se observa un efecto predominante en favor a la baja saturación, lo cual coincide con hallazgos previos (Kwallek et al., 1996). También existen estudios que sugieren que los tonos fríos pueden beneficiar a los estudiantes (Llinares et al, 2021a; Mahnke, 1996), pero parece que esto puede depender de la dificultad de la tarea y el nivel educativo del sujeto (Barrett et al., 2013; Mahnke, 1996). Finalmente, en cuanto a las dimensiones físicas identificadas en la optimización destacar que se trata de los valores de altura y anchura más elevados, lo que podría tener relación con la preferencia ante espacios más amplios (Hur et al., 2010).

Los resultados de este análisis subrayan que, entre las variables consideradas, el color y la iluminación muestran una mayor interrelación en entornos educativos. Es decir que cada uno puede modular o influir en los efectos del otro sobre la atención, la memoria y la preferencia, mientras que las dimensiones físicas del aula parecen tener una influencia más constante e independiente. Desde un punto de vista biológico existen razones que pueden justificar esta diferencia, a pesar de que las células especializadas en la percepción de la profundidad o dimensión no son necesariamente diferentes de las células responsables de percibir el color y la iluminación (todas forman parte del sistema visual y trabajan juntas para procesar la información visual). En primer lugar, el color y la iluminación son características visuales directamente relacionadas con la estimulación de células especializadas en la retina, como los conos y los bastones, que transmiten información visual directamente a la corteza visual (Gegenfurtner, 2003; Joukal, 2017), pudiendo tener un impacto más inmediato y específico en la percepción de dichas características. Sin embargo, la percepción de la dimensión implica procesos más complejos en los que se integran múltiples señales visuales y que ocurren en áreas específicas del cerebro después de que la información ha sido transmitida desde la retina a la corteza visual (Bear et al., 2016; Joukal, 2017). Estos procesos de integración y análisis más complejos pueden ser menos influenciados directamente por las características físicas simples como el color y la iluminación.

Con todo ello, se hace evidente la necesidad de una aproximación holística del paradigma espacio-persona. Ello implica tanto el concepto del diseño, considerando que el procesamiento visual de las personas se centra principalmente en la totalidad del entorno (Han et al., 2021), como el concepto de la persona, dentro de su contexto más amplio (Haynes, 2009) y también en el contexto educativo (Gadais et al, 2019). Esta perspectiva integradora es crucial, ya que la interacción entre el diseño espacial y los procesos cognitivos tiene un impacto directo en el aprendizaje y el bienestar de los estudiantes.

## 3. Implicación del género en el impacto del diseño

El efecto del diseño de un espacio en la persona está mediado por el género. De acuerdo a los resultados hallados, la percepción del color, la luz y dimen-



sión de un espacio es diferente entre hombres y mujeres, y la influencia que ello tiene en el aprendizaje también. Esta divergencia de la cognición de hombres y mujeres puede atribuirse a diversas razones específicas para cada uno de los tres elementos estudiados.

En primer lugar, las diferencias en la percepción e influencia del color en los estudiantes puede estar relacionada con la mayor pérdida de fotopigmento de conos en hombres frente a mujeres, lo que resulta en una menor sensibilidad a los colores rojos y verdes (Delpero et al., 2005). Esta discrepancia posiblemente se origina por la variación en la exposición a hormonas esteroides gonadales durante el desarrollo embrionario (Handa & McGivern, 2015). En segundo lugar, tales diferencias en los receptores visuales también podrían explicar las discrepancias en la influencia de la luz en cuanto al género. Además, estudios adicionales han demostrado diferencias en el ritmo circadiano, sugiriendo que los hombres poseen un sistema más flexible (Natale & Danesi, 2002), mientras que las mujeres son más sensibles a la luz brillante (Chellappa et al., 2017; Vidafar et al., 2024). En tercer lugar, la discriminación entre líneas y ángulos, como medida de percepción espacial, es más precisa en hombres (Collaer & Nelson, 2002) lo cual puede explicar las diferencias de genero que también se encuentran con respecto a la dimensión.

Asimismo, la relación con el espacio muestra diferencias de género en la propia orientación y en el uso de estrategias de navegación (Picucci et al., 2011). Estudios neurofisiológicos demuestran una mayor activación hipocampal durante la navegación espacial en hombres en comparación con mujeres (Grön et al., 2000). Estas discrepancias en la experiencia del espacio también pueden atribuirse a sesgos culturales y socioeconómicos relacionados con los roles sexuales esperados y/o la educación (Wood & Eagly, 2002), así como al uso de la realidad virtual como tecnología, que implica una mayor familiaridad por parte de los hombres (Rodríguez-Andrés et al., 2018; Sánchez-Cabrero et al., 2019; Terlecki & Newcombe, 2005). Esto último puede explicar que, en nuestro estudio, el rendimiento cognitivo de las mujeres en la prueba de memoria fue en general inferior al de los hombres.

Por lo tanto, estas discrepancias pueden deberse a factores biológicos, psicológicos, culturales e incluso a la naturaleza misma de la tarea cognitiva. Es fundamental reconocer que los grupos de participantes en la investigación deben ser equitativos para representar adecuadamente a ambos géneros. Solo de esta manera sería posible identificar y abordar, de manera rigurosa, las posibles desigualdades del impacto del diseño en hombres y mujeres. El análisis detallado de parámetros específicos, como las diferencias en la percepción, preferencias y procesamiento cognitivo, permitirá detectar y corregir cualquier sesgo o falta de inclusión en el diseño y planificación de espacios.

## 4. Implicación de la metodología propuesta

Una de las contribuciones más relevantes del presente trabajo radica en la metodología propuesta. Así, se plantea un método capaz de analizar los procesos cognitivos de los alumnos ante diferentes configuraciones de diseño. En este proceso adquiere un papel esencial tanto el espacio a evaluar como la medición psicológica de los sujetos.

En lo que se refiere al espacio a evaluar la realidad virtual ofrece beneficios clave al proporcionar una experiencia inmersiva y controlada del entorno espacial (Karakas & Yildiz, 2020; Latini et al., 2021). Esta tecnología permite manipular variables ambientales de manera precisa y repetible, lo que facilita la evaluación de cómo diferentes configuraciones espaciales afectan a la percepción y el comportamiento de las personas. De acuerdo con otros estudios, es una herramienta ampliamente aceptada en la investigación sobre este ámbito (Armougum et al., 2019; Higuera-Trujillo et al., 2017; Llinares et al., 2023; Marín-Morales et al., 2019) ya que tiene la capacidad de generar un espacio que la persona perciba como real (Barranco et al., 2023; Lehman & Conceição, 2010).

En cuanto a la medición psicológica, destacar las herramientas seleccionadas para la medición del rendimiento cognitivo. La elección de tareas auditivas para abordar la memoria y atención de los alumnos es crucial en este contexto. Al emplear tareas auditivas, se minimiza la interferencia con la experiencia visual proporcionada por la realidad virtual. Esto asegura que los participantes puedan concentrarse plenamente en la simulación espacial sin distracciones visuales adicionales, permitiendo así una evaluación más precisa de la respuesta cognitiva ante estímulos espaciales. Además, esta medición psicológica también permitió resaltar implicaciones específicas a nivel cognitivo, observándose que el diseño del espacio no influye de manera uniforme en los diferentes procesos cognitivos de los usuarios. En este contexto, de las tres métricas analizadas, la atención sostenida mostró ser especialmente influenciada por las intervenciones de diseño en el entorno educativo. Una posible explicación podría ser la sobrecarga resultante de la activación simultánea de la atención hacia estímulos externos (como los presentados en realidad virtual) e internos (hacia las tareas), lo cual podría haber saturado el sistema atencional en su conjunto. Aunque la atención externa y la interna operan a través de redes neuronales distintas, comparten conexiones que, en determinadas condiciones, pueden interferir negativamente con sus funciones (Maillet et al., 2019). Por lo tanto, el propio aspecto físico del aula cobra especial importancia ya que puede estar ejerciendo un efecto distractor sobre la atención (Rodrigues & Pandeirada, 2015). Además, si bien se demostró que todos los cambios en los elementos de diseño del entorno afectaron los niveles de atención, las preferencias fueron particularmente sensibles a los cambios en la iluminación. Que los cambios en los niveles de iluminación sean especialmente perceptibles puede deberse a un mecanismo de adaptación y supervivencia. Se ha demostrado que la iluminación tiene un papel importante en la fisiología humana (Pilorz et al., 2018) y, en particular, está muy implicada en el funcionamiento de mecanismos biológicos, como los ritmos circadianos (Tähkämö et al., 2019).

Esta doble ventaja -la del control del entorno y la medición de la respuesta del sujeto- permite en el área de la arquitectura identificar los atributos de diseño que favorezcan la respuesta de los sujetos, lo que presenta implicaciones en el estudio de la influencia del espacio en la percepción y cognición humana. Ofrece la posibilidad de abordar de manera más efectiva la percepción espacial y sus implicaciones en la vida cotidiana, contribuyendo a atender a la interdisciplinariedad que este ámbito de estudio requiere. Desde un punto de vista más práctico, la integración de esta metodología en el proceso de diseño puede aportar información de valor para el diseñador. .

## 5.limitaciones y futuras investigaciones

A pesar de las fortalezas de la metodología utilizada, es importante reconocer ciertas limitaciones que podrían afectar la generalización y el alcance de los hallazgos. Estas limitaciones se plantean atendiendo a dos niveles: a los instrumentos empleados (RV y tareas psicológicas) y a la muestra de participantes. Una de estas limitaciones radica en el uso de la realidad virtual, que podría introducir una brecha digital debido a las diferencias en la familiaridad y accesibilidad tecnológica entre los participantes (Rodríguez-Andrés et al., 2018; Sánchez-Cabrero et al., 2019). Esta disparidad podría influir en los datos recopilados y en la interpretación de los resultados. Hay que tener en cuenta que, con el paso del tiempo, es probable que esta brecha se reduzca. Otra limitación es la falta de variedad en las tareas utilizadas para abordar la memoria y la atención. La inclusión de una gama más diversa de tareas cognitivas (Sörqvist & Marsh, 2015; Sörqvist et al., 2016) podría proporcionar una comprensión más completa de cómo diferentes aspectos de la cognición interactúan con el espacio construido. Además, es esencial tener en cuenta que esta investigación se centró exclusivamente en estudiantes universitarios, lo que limita la generalización de los resultados a otros grupos demográficos. No obstante, estas limitaciones han sido tenidas en cuenta desde el planteamiento inicial por lo que no condenan la rigurosidad de los métodos ni de los resultados obtenidos. Reconocerlas permite orientar futuras investigaciones para ampliar y profundizar en los hallazgos aquí presentados, abriendo nuevas líneas de estudio que consideren una mayor diversidad de participantes y tareas.

Por lo tanto, una dirección prometedora de futuras investigaciones podría ser analizar el diseño de interiores en relación con elementos específicos, como carteles u otros objetos visuales. De acuerdo a ello, estudios como el de Cheryan y colaboradores (2014) determinan que es de interés comprender cómo estos elementos influyen en la percepción del espacio y el bienestar emocional de las personas. Dentro del ámbito de la arquitectura, también sería de interés estudiar variables de otras modalidades como, por ejemplo, los olores (Higuera-Trujillo et al., 2020) que son elementos compatibles con la RV. Además, considerando el empleo masivo de estímulos visuales en la educación, como PowerPoints y otros recursos gráficos, en detrimento de la enseñanza oral, es crucial investigar la atención visual. Esta línea de investigación ayudaría a comprender mejor cómo la saturación de estímulos visuales afecta la concentración y el aprendizaje de los estudiantes. Por su parte, otras líneas de investigación deberían ampliar la muestra para incluir diferentes niveles educativos y considerar la neurodiversidad incluyendo estudiantes no neurotípicos con características específicas como el trastorno por déficit de atención e hiperactividad (Rizzo et al., 2000) y así explorar cómo la percepción espacial y el entorno afectan a individuos con diversas necesidades cognitivas .

# Capítulo 8.
## Conclusiones / Conclusions

### 1. Conclusiones finales

El objetivo de esta memoria doctoral es analizar cómo diferentes aspectos físicos de un aula influyen en la cognición de los estudiantes. Para ello, se han llevado a cabo tres estudios publicados en revistas científicas de alto impacto indexadas en JCR, cada uno con objetivos específicos. El primero investigó el impacto relativo de los cambios en la luz, el color y la dimensión del aula sobre la atención, la memoria y la percepción de hombres y mujeres. El segundo estudio profundizó en cómo parámetros específicos de luz, color y dimensión afectan la memoria de hombres y mujeres, para minimizar las diferencias entre ellos. Finalmente, el tercer estudio abordó la relación entre diseño y cognición desde una perspectiva matemática, determinando las mejores combinaciones posibles de diseño para optimizar los procesos de atención, memoria y percepción. De esta forma, los resultados obtenidos de los tres estudios suponen un avance prometedor para la investigación del diseño arquitectónico centrado en el sujeto y, concretamente, para el diseño de aulas universitarias centradas en los estudiantes que hacen uso de ella.

Así, a partir del primer estudio se establece que la iluminación es el elemento de diseño que más afecta tanto a la percepción (en términos de preferencia), como a la atención y al rendimiento de la memoria. El color y la dimensión presentan menor incidencia que la iluminación, afectando únicamente a la atención de las mujeres. La evidencia presentada en este estudio plantea dos conclusiones principales: (1) debería priorizarse la luz en el proceso de diseño de un aula, o su modificación en aulas ya existentes, porque es el elemento que más afecta al aprendizaje y (2) un diseño de aula centrado en el alumnado requiere el uso de instrumentos que permitan medir diversos aspectos del propio estudiante, teniendo en cuenta su complejidad, ya que el entorno no influye de la misma manera en la cognición humana.

Por su parte, los resultados del segundo estudio, profundizan en los valores de diferentes parámetros de los elementos de diseño. A partir de ello se concreta que las aulas con iluminancia de 100lx, CCT de 6500K, alto de 3.8m, ancho de 7.2m, una saturación baja y un tono azul (Munsell, 5B), pueden plantearse como un diseño que favorece la memoria de los alumnos sin crear diferencias entre géneros. De igual forma que en el primer estudio, de estos hallazgos se desprenden dos conclusiones: (1) el género media la influencia del entorno en la cognición, por tanto es esencial incluir esta perspectiva para poder generar espacios inclusivos en cuanto a esta variable y (2) la influencia desigual de los diferentes parámetros del aula en la memoria sugiere la existencia de una interrelación entre ellos. Esto, sumado a la naturaleza del aula en la que los parámetros no se presentan de forma aislada, resalta la necesidad de considerar el conjunto de parámetros de los elementos del aula de manera integral al diseñar el espacio.

De acuerdo a estos dos artículos, se justifica el desarrollo del tercero que aborda el conjunto de elementos del diseño con el conjunto de procesos cognitivos estudiados. En términos prácticos, los resultados recomiendan ciertas combinaciones óptimas para favorecer los niveles de atención, memoria y preferencia de todo el alumnado. Por ejemplo, una iluminancia de 100lx, CCT de 6500K, alto de 4.4m, ancho de 8.4m, una saturación baja y un tono de azul (Munsell, 5B) o morados (Munsell, 5P/5PB), demostró ser efectiva en este sentido. También se pudo evidenciar que la misma combinación del tono morado con una iluminancia de 300lx, un alto de 3.2 o 4.4m y ancho de 6 o 8.4m, respectivamente, supone unos niveles de memoria y atención aún más elevados. Con ello se concluye que existe una doble complejidad, tanto por parte del espacio como del usuario, ya que la relación de los diferentes elementos de diseño con los diferentes procesos cognitivos no siguen un patrón único, debiendo ser abordado en su conjunto.



Adicionalmente de las conclusiones extraídas a partir de cada estudio, es relevante mencionar una conclusión común a todos ellos. A lo largo de todo el trabajo se ha consolidado una valiosa metodología que comprende el uso combinado de herramientas de presentación de espacios y de medición cognitiva del usuario. Por un lado, la realidad virtual como herramienta de visualización válida para estudiar el impacto que tiene el diseño en la cognición humana, permitiendo modificar el entorno estudiado controlando otras variables. Por su parte, el uso de tareas psicológicas aceptadas por la comunidad científica y de formulación de preguntas sobre la percepción cuantificables, son instrumentos de evaluación compatibles con la realidad virtual que permiten una aproximación al usuario disminuyendo la subjetividad.

A la luz de todo lo expuesto, resulta evidente que las conclusiones de los resultados tienen su principal interés a dos niveles: científico y práctico. Desde una perspectiva científica, los hallazgos contribuyen significativamente al conocimiento de cómo los elementos y parámetros espaciales del aula influyen en los procesos cognitivos de los estudiantes. Al identificar las diversas configuraciones y características del entorno que impactan en la cognición, se abre un nuevo campo de estudio que puede enriquecer la comprensión de la relación entre los ambientes educativos y el aprendizaje del estudiante. Desde una perspectiva práctica, estos resultados son de interés tanto para los diseñadores de espacios educativos como para los docentes. Para los diseñadores, la investigación proporciona una valiosa guía para la formulación de directrices específicas en el diseño de aulas universitarias que favorezcan el aprendizaje. Asimismo, a lo largo de todos los estudios, se ha consolidado una valiosa metodología que se presenta como complementaria para los profesionales del diseño arquitectónico. Con ella se consigue una aproximación al usuario desde una perspectiva objetiva, favoreciendo la implementación de nuevos enfoques de trabajo más dirigidos a las necesidades reales de las personas que utilizarán los espacios. Esta nueva perspectiva tiene el potencial de mejorar la calidad de los proyectos arquitectónicos y, en última instancia, de optimizar la funcionalidad del espacio construido. Por otro lado, para los docentes, este estudio ofrece información anticipada sobre cómo las condiciones del aula influyen en los estudiantes. Este conocimiento les puede ser de utilidad para ajustar sus metodologías de enseñanza y así aprovechar al máximo el entorno en el que imparten clases.

Junto a estos intereses científicos y prácticos, los resultados suponen una transferencia del conocimiento a otros niveles: empresarial-económico y social. Por su parte, los resultados permiten alcanzar una posición de liderazgo empresarial. Desde este punto de vista, se abren tanto líneas de negocio relacionadas con la consultoría, formación y divulgación, como líneas de desarrollo de productos concretos. Así, los espacios educativos validados científicamente, basados en los hallazgos de la investigación, tienen el potencial de ser altamente valorados en el mercado. Al demostrar que estos espacios pueden mejorar la memoria, la atención y la preferencia de los estudiantes, se crea una ventaja competitiva para las empresas y organizaciones que se dedican al diseño y construcción de entornos educativos. Además, al promover el desarrollo de estos espacios, se puede aumentar la eficacia y la productividad del proceso de aprendizaje, lo que a su vez puede tener un impacto positivo en la economía en general. Por último, a nivel social, se fomenta el uso de espacios de aprendizaje inclusivos, lo cual es fundamental para minimizar las disparidades en el rendimiento educativo entre diferentes grupos de estudiantes. Al diseñar espacios “pensandos en todos”, se promueve la equidad en la educación y se crea un entorno que apoya el éxito de todos los estudiantes, independientemente de su género u otras características personales. Esto no solo beneficia a los individuos, sino que también supone una importante transferencia del conocimiento a la sociedad ya que contribuye a que sea más justa y cohesionada en su conjunto.

En definitiva, los espacios desempeñan un papel fundamental en nuestra vida diaria. Ello incluye la influencia que el entorno educativo, como el aula, tiene en la cognición del alumnado. Por lo tanto, la comprensión y profundización en esta relación es crucial, tanto para el ámbito de estudio del diseño (arquitectura, edificación o ingeniería, entre otros) como del ser humano (psicología, biología o



medicina, entre otros). El enfoque y metodología usada en este trabajo puede ser prometedor ya que supone un comienzo de multidisciplinariedad en el que se unen las dos áreas de conocimiento. Por ello, es de esperar que el presente trabajo marque un nuevo paso en esa dirección.

## 2. Last Conclusions

The objective of this doctoral dissertation is to analyze how different physical aspects of a classroom influence students' cognition. To this end, three studies have been conducted and published in high-impact scientific journals indexed in the JCR, each with specific objectives. The first study investigated the relative impact of changes in light, color, and classroom dimensions on the attention, memory, and perception of men and women. The second study delved into how specific parameters of light, color, and dimensions affect the memory of men and women, aiming to minimize differences between them. Finally, the third study addressed the relationship between design and cognition from a mathematical perspective, determining the best possible design combinations to optimize attention, memory, and perception processes. Thus, the results obtained from the three studies represent a promising advancement for research in subject-centered architectural design, specifically for the design of student-centered university classrooms.

From the first study, it is established that lighting is the design element that most affects both perception (in terms of preference) and attention and memory performance. Color and dimension have less impact than lighting, affecting only women's attention. The evidence presented in this study leads to two main conclusions: (1) lighting should be prioritized in the classroom design process or in modifying existing classrooms because it is the element that most affects learning, and (2) student-centered classroom design requires the use of tools to measure various aspects of the student, considering their complexity, as the environment does not influence human cognition uniformly.

The second study results further detail the values of different design element parameters. It concludes that classrooms with an illuminance of 100lx, CCT of 6500K, height of 3.8m, width of 7.2m, low saturation, and a blue hue (Munsell 5B) can be considered a design that favors students' memory without creating gender differences. Similar to the first study, these findings lead to two conclusions: (1) gender mediates the influence of the environment on cognition, thus it is essential to include this perspective to generate inclusive spaces concerning this variable, and (2) the unequal influence of different parameters on memory suggests an interrelationship between them. This, combined with the nature of the classroom where parameters are not presented in isolation, highlights the need to consider the set of classroom element parameters integrally when designing the space.

Based on these two articles, the development of the third, which addresses the set of design elements with the set of studied cognitive processes, is justified. Practically, the results recommend certain optimal combinations to enhance students' attention, memory, and preference levels. For example, an illuminance of 100lx, CCT of 6500K, height of 4.4m, width of 8.4m, low saturation, and a hue of blue or purple proved effective in this regard. It was also evidenced that the same purple hue combination with an illuminance of 300lx, a height of 3.2 or 4.4m, and a width of 6 or 8.4m respectively, results in even higher memory and attention levels. Thus, it is concluded that there is a dual complexity, both in terms of space and the user, as the relationship of different design elements with different cognitive processes does not follow a single pattern and must be addressed as a whole.

In addition to the conclusions drawn from each study, it is relevant to mention a common conclusion across all of them. Throughout the work, a valuable methodology has been consolidated, comprising the combined use of space presentation tools and cognitive user measurement. On one hand, virtual reality as a visualization tool is valid for studying the impact of design on human cognition, allowing the modification of the studied environment while controlling other variables. On the other hand, the use of psychologically accepted tasks by the scientific community and quantifiable perception questions are evaluation tools compatible with virtual reality, enabling an approach to the user that reduces subjectivity.



In light of all the above, it is evident that the conclusions of the results are of primary interest on two levels: scientific and practical. From a scientific perspective, the findings significantly contribute to understanding how classroom spatial elements and parameters influence students' cognitive processes. By identifying the various configurations and environmental characteristics that impact cognition, a new field of study is opened that can enrich the understanding of the relationship between educational environments and student learning. From a practical perspective, these results are of interest to both educational space designers and educators. For designers, the research provides valuable guidance for formulating specific guidelines in the design of university classrooms that favor learning. Additionally, throughout all the studies, a valuable methodology has been consolidated, presenting itself as complementary for architectural design professionals. It allows an objective approach to the user, favoring the implementation of new work approaches more focused on the real needs of those who will use the spaces. This new perspective has the potential to improve the quality of architectural projects and, ultimately, to optimize the functionality of the built environment. For educators, this study offers advanced information on how classroom conditions influence students. This knowledge can be useful for adjusting their teaching methodologies to make the most of the environment in which they teach.

Alongside these scientific and practical interests, the results represent a knowledge transfer to other levels: business-economic and social. From a business standpoint, the results enable achieving a leadership position. From this viewpoint, business lines related to consulting, training, and dissemination, as well as the development of specific products, are opened. Scientifically validated educational spaces, based on research findings, have the potential to be highly valued in the market. By demonstrating that these spaces can improve students' memory, attention, and preference, a competitive advantage is created for companies and organizations dedicated to designing and constructing educational environments. Furthermore, promoting the development of these spaces can increase the efficiency and productivity of the learning process, which can, in turn, have a positive impact on the economy in general. Lastly, on a social level, the use of inclusive learning spaces is encouraged, which is essential for minimizing disparities in educational performance among different student groups. Designing spaces "with everyone in mind" promotes educational equity and creates an environment that supports the success of all students, regardless of their gender or other personal characteristics. This benefits not only individuals but also represents significant knowledge transfer to society, contributing to making it more just and cohesive as a whole.

In short, spaces play a fundamental role in our daily lives. This includes the influence that the educational environment, such as the classroom, has on students' cognition. Therefore, understanding and delving into this relationship is crucial, both for the field of design study (architecture, construction, engineering, among others) and for the human being (psychology, biology, medicine, among others). The approach and methodology used in this work can be promising as they represent the beginning of multidisciplinarity, combining the two fields of knowledge. Thus, it is expected that this work marks a new step in that direction.

# Actividades de investigación

La elaboración de esta Memoria Doctoral implicó diversas actividades de investigación, entre las que se encuentran los tres artículos recogidos en los capítulos 4 a 6. En todas ellas se aplicó el mismo procedimiento, consolidando así una metodología centrada en el usuario para estudiar la temática principal abordada: el análisis de la influencia de la arquitectura en la cognición del ser humano. Con ello, se ha pretendido hacer una aportación a la arquitectura desde el ámbito de la psicología, favoreciendo la aproximación entre ambas.

## Proyectos de investigación / Research projects

*Fortalecimiento de las capacidades de agentes claves para la promoción de la transferencia e inclusión de conocimiento innovador en el ámbito del planeamiento territorial y urbano ecológico dentro del marco formativo de grado y posgrado (V.17.14.03).* Domingo Sanchez Fuentes. Universidad de Sevilla (01/01/17 – 31/12/17, 15.000,00 €). Periodo anterior a la Tesis.

*Ayuda predoctoral FPU-Nole Fajardo: el diseño del aula para potenciar los procesos cognitivos del alumnado: una propuesta metodológica para potenciar los procesos cognitivos del alumnado. Una propuesta metodológica para evaluar las variables luz, color y forma (FPU19/03531).* Llinares Millán, María del Carmen. Ministerio de universidades e Investigación (31/10/20 a 31/10/24, 90.091,91 €)

*Nuevos retos en neuroarquitectura: Desarrollo de herramientas de validación de la realidad virtual y de mediación del estado emocional de los sujetos. (CIAICO/2022/031).* Llinares Millán, María del Carmen. Generalitat Valenciana (01/01/23 a 31/12/25, 90.000,00 € )

*Vivienda y bienestar: modelo afectivo-emocional para el estudio y diseño de los espacios residenciales. (PAID-06-22).* Higuera Trujillo, Juan Luis. Universitat Politècnica de València (01/01/23 –a 30/06/24, 11.987,80 €).

*Propuesta metodológica para la identificación de los atributos vinculados al bienestar en el diseño de la vivienda(PID2022-136582OB-I00).* Llinares Millán, María del Carmen. Agencia Estatal de Investigación (01/09/23 a 31/08/26, 156.375,00 €).

*Neuroarquitectura aplicada al disseny d'habitatges industrialitzats* (HBIRT3-2023-7). Llinares Millán, María del Carmen. Generalitat Valenciana (01/12/23 – 30/09/24, 50.000,00 €).

*Desarrollo de una aplicación de RV-RA para el estudio de estrategias de modificación de la percepción espacial mediante la utilización de anamorfismos (PAID-06-23).* Martín Fuentes, Daniel Vicente. Universitat Politècnica de València (01/01/24 a 31/12/25, 6.000,00 € )

## Estancia de investigación / Research internship

Dipartamento di neuroscience, riabilitazione, oftalmología, genética e scienze materno-infantili (Dinogmi), Università dedli studi di Genova, Genova. Angelo Schenone. (01/09/23 – 30/11/23).

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**Nolé, M. L.,** Soler, D., Higuera-Trujillo, J. L., & Llinares, C. (2022). Optimization of the Cognitive Processes in a Virtual Classroom: A Multi-objective Integer Linear Programming Approach. Mathematics, 10(7), 1184. https://doi.org/10.3390/math10071184

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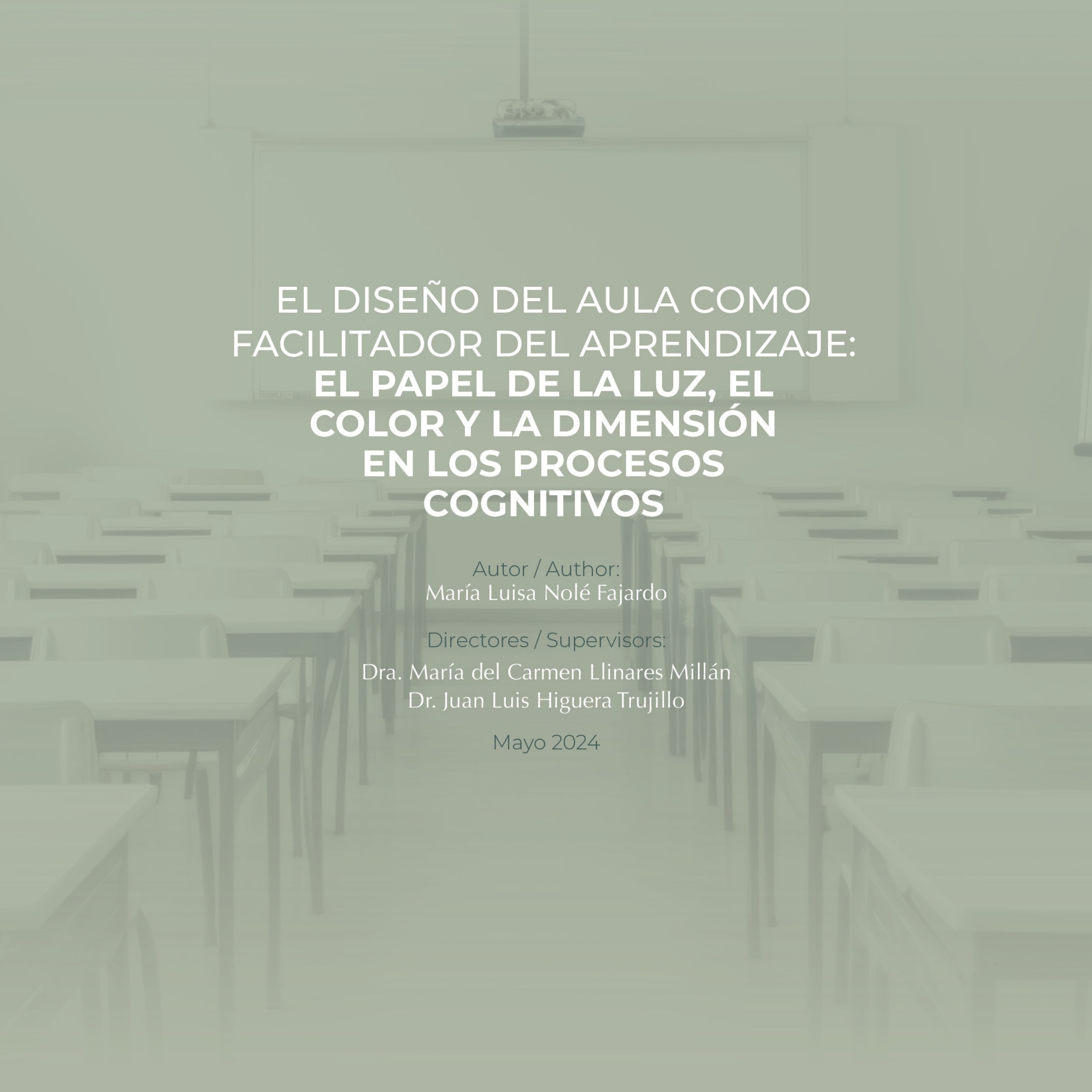

# EL DISEÑO DEL AULA COMO FACILITADOR DEL APRENDIZAJE: **EL PAPEL DE LA LUZ, EL COLOR Y LA DIMENSIÓN EN LOS PROCESOS COGNITIVOS**


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