

Key aspects for evaluating user experience using eye tracking in immersive educational virtual reality environments

Aspectos clave para la evaluación de experiencia de usuario usando eye tracking en entornos inmersivos educativos de realidad virtual

Aspectos-chave para avaliar a experiência do usuário utilizando rastreamento ocular em ambientes de realidade virtual educacional imersiva

Maria Fernanda Martínez Moreno¹
 Angie Carolina Gómez Acosta²
 Sandra Milena Roa Martínez³

Received: September 1st, 2025

Accepted: December 10th, 2025

Available: January 13th, 2026

How to cite this article:

M. F. Martínez-Moreno, A. C. Gómez-Acosta, and S. M. Roa-Martínez, “Key aspects for evaluating user experience using eye tracking in immersive educational virtual reality environments,” *Revista Ingeniería Solidaria*, vol. 22, no. 1, 2026.
 doi: <https://doi.org/10.16925/2357-6014.2026.01.04>

Review article. <https://doi.org/10.16925/2357-6014.2026.01.04>

¹ Grupo de Investigación en Inteligencia Computacional – GICO, Universidad del Cauca, Facultad de Ingeniería Electrónica y Telecomunicaciones, Colombia.

E-mail: mafemartinez@unicauca.edu.co.

ORCID: <https://orcid.org/0009-0006-1255-0829>.

CvLAC: https://scienti.minciencias.gov.co/cvlac/visualizador/generarCurriculoCv.do?cod_rh=0002408449

² Grupo de Investigación en Inteligencia Computacional – GICO, Universidad del Cauca, Facultad de Ingeniería Electrónica y Telecomunicaciones, Colombia.

E-mail: angiecgomez@unicauca.edu.co.

ORCID: <https://orcid.org/0009-0000-0781-6799>.

CvLAC: https://scienti.minciencias.gov.co/cvlac/visualizador/generarCurriculoCv.do?cod_rh=0002408531

³ Grupo de Investigación en Inteligencia Computacional – GICO, Universidad del Cauca, Facultad de Ingeniería Electrónica y Telecomunicaciones, Colombia.

E-mail: smroa@unicauca.edu.co.

ORCID: <https://orcid.org/0000-0002-2271-6101>.

CvLAC: https://scienti.minciencias.gov.co/cvlac/visualizador/generarCurriculoCv.do?cod_rh=0000232211



Abstract

Introduction: The article is the result of the research "User Experience Evaluation in Educational Immersive Virtual Reality Environments with Eye Tracking," conducted at the University of Cauca in 2025.

Problem: Traditional methods fail to capture visual attention and cognitive load in real time, making it difficult to compare results.

Objective: To identify and map approaches, trends, and eye-tracking metrics in UX evaluation for immersive VR educational environments, in order to pinpoint gaps and opportunities for more consistent, user-centered evaluation models.

Methodology: Systematic review using the SALSA framework (protocol, application, and analysis), with scope defined by PICOC, focusing on population, intervention, outcomes, and the immersive educational context.

Results: Metrics such as fixations, gaze trajectory, saccades, and pupilometry are highlighted, combined with subjective instruments. Challenges include small sample sizes, calibration issues, and symptoms of fatigue and cybersickness.

Conclusion: A standardized methodological framework is needed, combining eye-tracking metrics with subjective perceptions. While eye tracking is increasingly being adopted, gaps remain in sample sizes, cybersickness control, and experience duration.

Originality: Provides an updated synthesis of the intersection between immersive VR educational environments and eye tracking, with a mapping of technologies, metrics, and methods, and highlights gaps to improve future frameworks and studies.

Limitations: Variability in configurations and protocols, small sample sizes, calibration issues, visual fatigue, cybersickness, and conflicts between experimental control and naturalness.

Keywords: User experience, virtual reality, eye tracking, evaluation, systematic review.

Resumen

Introducción: El artículo es producto de la investigación "Evaluación de la experiencia de usuario en entornos inmersivos educativos de realidad virtual con uso de *eye tracking*" desarrollada en la Universidad del Cauca en el año 2025.

Problema: Los métodos tradicionales no capturan atención visual ni carga cognitiva en tiempo real y dificultan la comparación de resultados.

Objetivo: Identificar y mapear enfoques, tendencias y métricas de *eye tracking* en la evaluación de la UX en entornos educativos de RV inmersiva, para identificar vacíos y oportunidades para modelos de evaluación más consistentes y centrados en el usuario.

Metodología: Revisión sistemática usando el marco SALSA (protocolo, aplicación y análisis), con el alcance delimitado por PICOC, enfocándose en población, intervención, resultados y contexto educativo inmersivo.

Resultados: Se destacan métricas como fijaciones, trayectoria de mirada, sacádicos y pupilometría, combinadas con instrumentos subjetivos. Los retos incluyen tamaños muestrales pequeños, problemas de calibración y síntomas de fatiga y *cybersickness*.

Conclusión: Se necesita un marco metodológico estandarizado que combine métricas oculares y percepciones subjetivas. Aunque el *eye tracking* se está adoptando más, persisten vacíos en tamaños muestrales, control de *cybersickness* y duración de las experiencias.

Originalidad: Ofrece una síntesis actualizada sobre la intersección de entornos educativos de RV inmersiva y *eye tracking*, con un mapeo de tecnologías, métricas y métodos, y señala los vacíos para mejorar futuros marcos y estudios.

Limitaciones: Variabilidad en configuraciones y protocolos, tamaños muestrales pequeños, problemas de calibración, fatiga visual, *cybersickness* y conflictos entre control experimental y naturalidad.

Palabras clave: Experiencia de usuario, realidad virtual, seguimiento ocular, evaluación, revisión sistemática.

Resumo

Introdução: Este artigo é produto do projeto de pesquisa "Avaliação da Experiência do Usuário em Ambientes Educacionais de Realidade Virtual Imersiva Utilizando Rastreamento Ocular", realizado na Universidade de Cauca em 2025.

Problema: Os métodos tradicionais não capturam a atenção visual ou a carga cognitiva em tempo real, dificultando a comparação de resultados.

Objetivo: Identificar e mapear abordagens, tendências e métricas de rastreamento ocular na avaliação da experiência do usuário em ambientes educacionais de realidade virtual imersiva, a fim de identificar lacunas e oportunidades para modelos de avaliação mais consistentes e centrados no usuário.

Metodologia: Foi realizada uma revisão sistemática utilizando o framework SALSA (protocolo, aplicação e análise), com o escopo definido pelo PICOC, com foco em população, intervenção, resultados e contexto educacional imersivo.

Resultados: Métricas como fixações, trajetória do olhar, sacadas e pupilometria, combinadas com instrumentos subjetivos, foram destacadas. Os desafios incluíram tamanhos de amostra pequenos, problemas de calibração e sintomas de fadiga e ciberenjoo.

Conclusão: É necessário um arcabouço metodológico padronizado que combine métricas de rastreamento ocular e percepções subjetivas. Embora o rastreamento ocular esteja sendo adotado de forma mais ampla, ainda existem lacunas em relação ao tamanho das amostras, ao controle da ciberenjoo e à duração da experiência.

Originalidade: Esta revisão oferece uma síntese atualizada da interseção entre ambientes educacionais de realidade virtual imersiva e rastreamento ocular, mapeando tecnologias, métricas e métodos, e destacando lacunas para aprimorar arcabouços e estudos futuros.

Limitações: Variabilidade nas configurações e protocolos, tamanhos de amostra pequenos, problemas de calibração, fadiga ocular, ciberenjoo e conflitos entre controle experimental e naturalidade.

Palavras-chave: Experiência do usuário, realidade virtual, rastreamento ocular, avaliação, revisão sistemática.

1. INTRODUCTION

The use of information and communication technologies (ICT) has progressively transformed learning environments, requiring changes in pedagogical methods and approaches [1]. Among these technologies, virtual reality stands out for its ability to create three-dimensional environments that allow the manipulation of objects, processes, and experiences that are difficult to visualize or understand in a traditional classroom setting [2], [3]. It is worth noting that immersive virtual reality offers a more natural and dynamic interaction between the user and the content, promoting

autonomous learning and critical thinking [4]. However, to make effective use of immersive environments, it is essential to consider the user experience as a key component of the design, based on the definition provided by ISO 9241-210:2019, where user experience (UX) encompasses emotions, beliefs, perceptions, and physical and psychological responses that arise during interaction with a system [5]. Its evaluation helps identify factors that impact satisfaction, performance, and accessibility, especially in technology-mediated educational scenarios. Currently, UX evaluation in immersive educational VR environments presents limitations, as most studies use traditional tools such as interviews or post-use questionnaires, which do not always adequately capture real-time visual interaction or user attention [6], [7]. Consequently, more precise methods like eye tracking have begun to be explored, allowing observation of how the user's attention is distributed within an environment, providing objective indicators of cognitive load and usability [8], [9]. Eye-tracking technology records metrics such as fixations, saccades, and heatmaps, which are useful for analyzing the user's visual behavior during the experience, without needing to interrupt or explicitly mediate their interaction with the system [10]. This is especially relevant in complex educational contexts, where the data obtained helps improve instructional design and adapt interfaces to the actual needs of the user [11]. Therefore, this paper presents a systematic review aimed at identifying and analyzing current approaches used in UX evaluation for immersive environments using eye-tracking technologies, in order to determine trends, gaps, and opportunities for the development of consistent, user-centered evaluation frameworks, as the literature in this area presents high methodological dispersion, a variety of technologies, and the absence of standardized frameworks for such evaluations, as will be discussed in the following section.

1.1 Literature review or research background

Several studies have addressed the evaluation of user experience (UX) in digital environments from multiple approaches. Among them is the work of Gorbunovs [12], who presents a review on the use of eye-tracking technology in digital learning environments. This study highlights how eye tracking allows the analysis of attention patterns, learning styles, and user behavior in educational platforms, providing valuable input for the design of adaptive learning objects. Gorbunovs also emphasizes the need to consider cultural, gender, and literacy factors in instructional designs based on gaze data, proposing future directions for the development of personalized digital tutoring models; however, it does not address immersive environments.

According to [13], “virtual reality enables users to access a wide range of experiences in safe, risk-free environments through playful activities, which positively enhances its role as a tool for the transmission of knowledge to individuals interacting within these settings.” Examples of such applications include learning alternating current electrical circuits [14]; the VRTBLOOM framework, designed for the creation of virtual reality learning activities (VRLAs), based on the first level of Bloom’s taxonomy [15]; and, along the same line, [16], which enables the design of tasks with varying levels of complexity to observe students’ learning styles. Finally, MARHATI is presented as a methodological framework that guides educators and developers in the design of authoring tools for immersive educational activities [17].

Complementarily, the study by Díaz-Oreiro et al. [18] provides a systematic review of the literature on the use of standardized questionnaires such as AttrakDiff, which measures the quality of the user experience in terms of attractiveness and preference [19]; UEQ (User Experience Questionnaire), which evaluates the user experience considering dimensions like attractiveness and usability [20]; and meCUE (mobile Experience Questionnaire), which focuses on the user experience with mobile devices [21]. The study analyzes a set of primary studies and addresses questions regarding usage frequency, geographical distribution, combination with other instruments, and application in non-traditional interfaces such as virtual reality or eye-tracking-based technologies. A growing use of UEQ and meCUE is observed in studies involving immersive interfaces, highlighting their relevance in evaluating experiences in environments that go beyond conventional graphical interfaces.

2. MATERIALS AND METHODS

As a methodological process, a systematic review was conducted, for which the SALSA framework (Search, Appraisal, Synthesis, and Analysis), proposed by Codina [22], was used. Its stages were adapted and aligned with the methodology of Petersen et al. [23], which proposes organizing mapping studies into three blocks: protocol definition, protocol application, and result analysis. Figure 1 presents the methodological flow adapted for conducting this review.

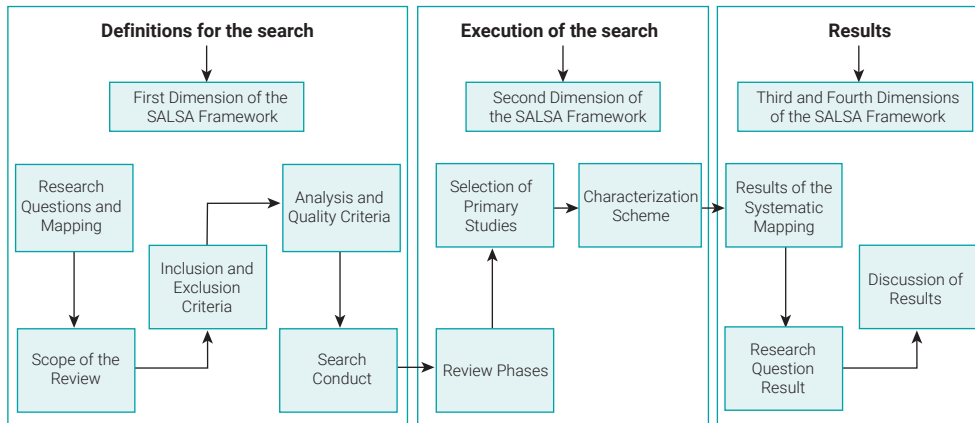


Figure 1. Methodological Process Flow of the Systematic Review.
Source: own work

The following describes each of the stages and activities proposed in the flow of the adapted methodological process.

2.1 Research Questions

This study was guided by six (6) research questions aimed at characterizing the use of eye tracking in the evaluation of user experience in immersive virtual reality educational environments:

- RQ1: What factors influence user perception and experience in immersive virtual reality educational environments?
- RQ2: How do metrics obtained through eye tracking contribute to the design and evaluation of interfaces in virtual reality environments?
- RQ3: What qualitative and quantitative evaluation methods are used to measure user experience in immersive virtual reality environments, and what is their impact on the accuracy of the results?
- RQ4: What are the limitations and technical challenges of using eye tracking technologies in virtual reality environments?
- RQ5: How can immersive virtual reality environments be optimized to reduce the incidence of cybersickness and other physical issues?
- RQ6: What models or frameworks have been developed to evaluate user experience in virtual reality environments?

2.2 Search Strategy: PICOC Method

To define the key search terms, the PICOC method [24] was applied, with its meaning, instantiation, and guiding question presented in *Table 1*.

Table 1. Description of the PICOC Method

Component	Help Question	Instantiation
(P) <i>Population</i>	Who?	Immersive virtual reality environments.
(I) <i>Intervention</i>	What? How?	Aspects of user experience evaluation.
(C) <i>Comparison</i>	What to compare with?	No comparison.
(O) <i>Outcomes</i>	What is sought to be achieved/ improved?	Identification of metrics for evaluating immersive virtual reality environments.
(C) <i>Context</i>	In what type of organization and under what circumstances?	Immersive virtual reality educational envi- ronments.

Source: own work

Based on the PICOC configuration, the following search string was constructed:

("user experience" OR "UX" OR "experience evaluation" OR "usability evaluation" OR "user satisfaction" OR "interaction assessment") AND ("virtual reality" OR "VR" OR "immersive environments" OR "immersive learning" OR "3D environments") AND ("eye tracking" OR "eye-tracking" OR "ocular tracking" OR "gaze tracking" OR "visual attention")

2.3 Selection and Filtering of Studies

The search was conducted in the Scopus database, yielding 204 initial documents, which were subjected to a selection process in two stages or filters:

First filter: application of inclusion criteria (IC) and exclusion criteria (EC), reducing the corpus to 82 documents.

Inclusion criteria:

- IC1: Publication between 2020–2024.
- IC2: Language in English or Spanish.
- IC3: Article, conference, or book chapter type.
- IC4: Open or institutional access available.

Exclusion criteria:

- EC1: Publications prior to 2020.
- EC2: Languages other than English/Spanish.
- EC3: No access to the full text.

Second filter: evaluation using seven (7) quality criteria (QC), which reduced the initial set to 22 studies.

Quality criteria:

- QC1: Does the work include aspects of user experience evaluation in immersive virtual reality educational environments?
- QC2: Does the study include a qualitative, quantitative, or both types of evaluation of user experience related to eye tracking?
- QC3: Does the work include or define eye-tracking metrics for user experience evaluation?
- QC4: Are the study limitations identified (such as potential sources of bias or technical challenges) in the use of eye tracking in virtual reality environments?
- QC5: Does the study include details about eye-tracking devices, virtual environments, and user experience evaluation criteria?
- QC6: Does the study address the type of virtual reality educational environment?
- QC7: Does the study present technical characteristics associated with the eye-tracking device that may influence user experience results?

2.4 Data Extraction and Synthesis

To proceed with the synthesis of the results, which will be described below, it is important to highlight that the 22 selected studies were categorized based on the devices used, technological integration, applied metrics, evaluation methods, and educational context. The results were organized to identify common patterns, thematic gaps, and relevant contributions to the design and evaluation of immersive educational experiences with eye tracking.

3. RESULTS

The set of primary studies was published between 2020 and 2024, including only peer-reviewed contributions (scientific journal articles and conference papers). Figure 2 illustrates the annual distribution of these studies, disaggregated by type of publication. The results show a noticeable peak in 2020 (six publications), mainly conference papers, followed by a decline in 2021. From 2022 onwards, there is a gradual recovery, stabilizing in 2023 and 2024 with five studies each, where journal articles gained more relative weight. This temporal trend highlights the initial surge of research interest in immersive virtual reality with eye tracking, particularly in conferences, and a subsequent phase of consolidation with increasing journal publications.

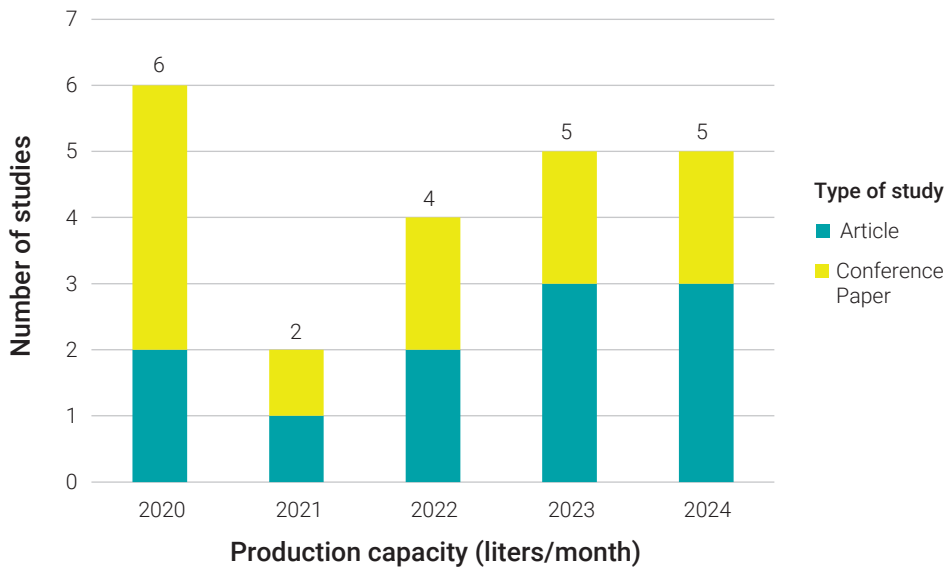


Figure 2. Annual distribution of primary studies by type of publication (2020–2024)
 Source: own work

3.1 Technologies Used

- 91% of the studies used HTC Vive Pro Eye headsets or similar devices with integrated eye tracking. *Figure 3* shows the distribution of head-mounted displays, highlighting the predominance of HTC Vive Pro Eye (70%), followed by Varjo VR-2 Pro/Aero (21%), and smaller shares corresponding to HTC Vive + Tobii add-ons (5%), Fove (2%), and other devices (2%).

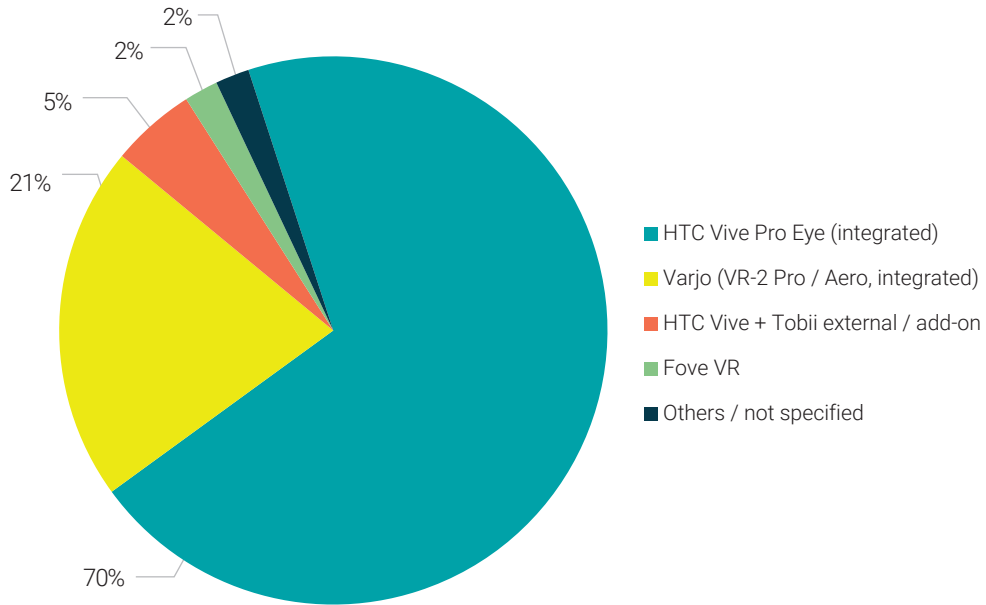


Figure 3. Distribution of head-mounted displays used across studies.

Source: own work

- Unity was the most commonly used development platform (68.2%), followed by SteamVR and OpenCV.
- Physiological sensors (such as GSR and PPG) were integrated in 45.5% of the studies, reflecting a trend towards multimodal approaches.

3.2 Thematic Approaches

The thematic approaches identified in the studies analyzed are presented in various ways. As shown in *Table 2*, the most addressed category was eye tracking and visual metrics, present in 90.9% of the studies (20 out of 22), reflecting a strong inclination towards the objective measurement of visual attention. This is followed by training and simulation at 36.4% (8 studies), and visualization and perception, along with cognitive evaluation and mental load, each at 27.3% (6 studies).

Table 2. Thematic Distribution of Primary Studies.

No. of Study	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	
Visualization and Perception	X		X						X					X						X	X		
Navigation and Locomotion		X															X	X					
Training and Simulation				X		X				X				X	X				X	X			X
Interface Design and Optimization							X					X			X								
Eye-Tracking and Eye Metrics	X	X	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Emotional Representation and Narrative				X	X				X										X			X	
Cognitive Evaluation and Mental Load				X		X						X					X	X			X		

Source: own work

The categories or dimensions with the lowest frequency were emotional representation and narrative (22.7%, 5 studies), navigation and locomotion (13.6%, 3 studies), and interface design and optimization (13.6%, 3 studies).

These figures reflect a general trend towards quantitative approaches focused on visual attention and cognitive load, while aspects such as narrative, emotion, or spatial interaction remain less explored in the immersive educational environments evaluated.

Metrics

The reviewed works revealed a combined use of objective and subjective metrics to evaluate user experience in digital environments. The most common include eye-tracking measures (fixations, saccades, visual trajectories) and qualitative methods such as interviews or standardized questionnaires such as the SUS (System Usability Scale), which assesses the ease of use of a system [25], the UEQ-S (User Experience Questionnaire - Short Version), a shortened version of the UEQ (User Experience Questionnaire) [26], and the NASA-TLX (Task Load Index), which is used to evaluate the perceived cognitive load during system interaction [27].

Quantitative Metrics

Among the quantitative metrics, fixations were the most frequently reported, appearing in 19 studies (86.4%), followed by visual trajectories (16 studies, 72.7%), saccades (13 studies, 59.1%), pupillometry (12 studies, 54.5%), and response time (9 studies, 40.9%). Figure 4 illustrates these results, highlighting the predominance of fixation-based analyses as the main quantitative indicator of visual attention.

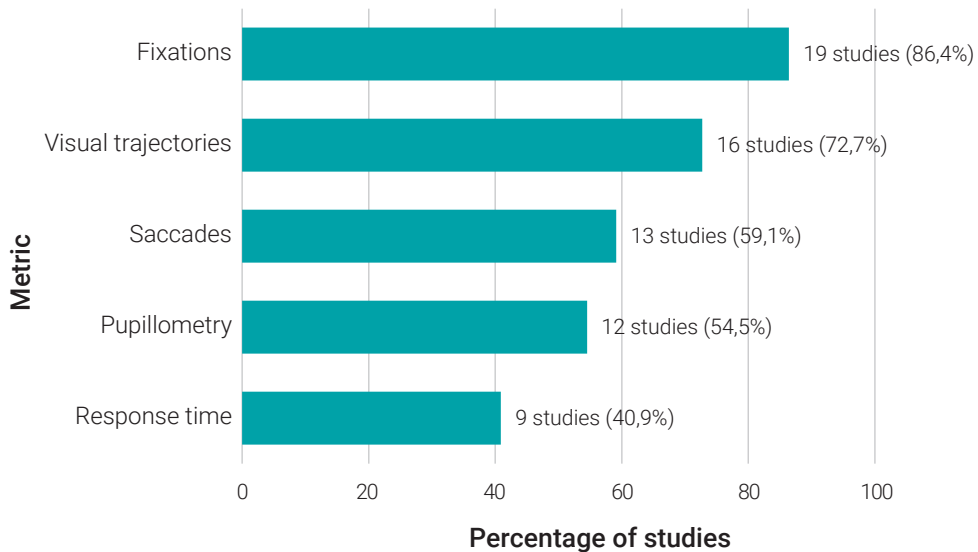


Figure 4. Quantitative metrics used across studies.

Source: own work

Qualitative Metrics

- Subjective instruments (questionnaires, interviews, direct observation): 68.2 %
- Physiological metrics (GSR, heart rate, among others): 45.5 %

Evaluation Methods

- 68% combined quantitative and qualitative methods.
- 59% applied standardized questionnaires such as SUS, NASA-TLX, or UEQ-S.
- 27% integrated physiological analysis with visual metrics to validate cognitive load.

Figure 5 complements these results by showing that mixed methods were the most prevalent, often combined with standardized questionnaires, while physiological/visual metrics appeared less frequently.

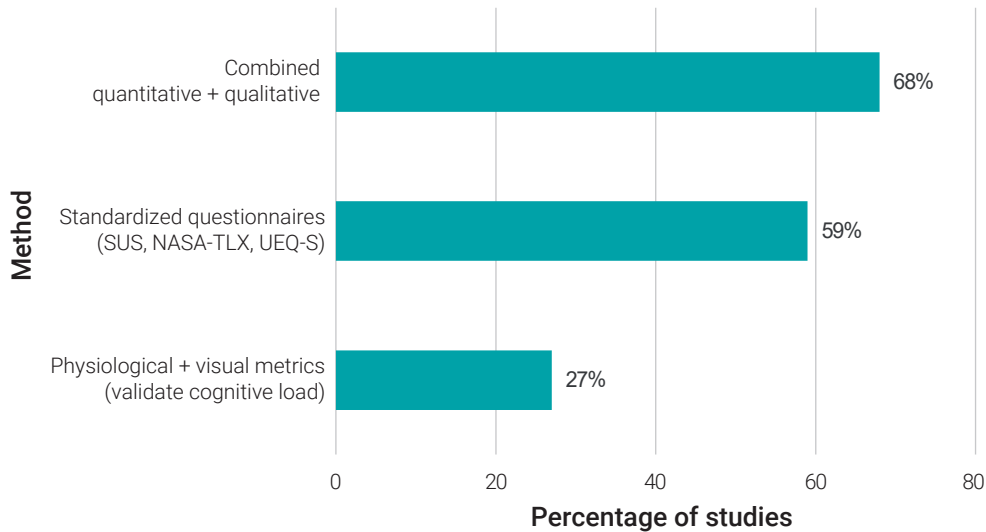


Figure 5. Evaluation methods applied across studies.

Source: own work

Identified Challenges

- 82% had small sample sizes (≤ 30 participants).
- 50% reported calibration or eye tracker accuracy issues.
- 41% mentioned visual fatigue or cybersickness as a limitation.
- 36% lacked realistic or prolonged scenarios.

Additionally, the lack of standardization in evaluation protocols, the technical complexity in data synchronization, and the need to consider cybersickness as an impact variable on UX were identified.

4. DISCUSSION

This section presents a detailed analysis of the findings from the selected studies, aiming to address the six research questions formulated in the systematic review. Each subsection synthesizes the patterns, contributions, and gaps identified in relation to

the key themes, providing a comparative discussion between the approaches and technologies used in evaluating user experience (UX) in immersive educational environments with eye tracking.

RQ1: What factors influence user perception and experience in immersive virtual reality educational environments?

The factors influencing user perception and experience in these environments include narrative design, the sense of immersion and presence, environment customization, and the use of technologies such as eye tracking. Narrative, understood as a structural element of immersive design, plays a fundamental role in contextualizing abstract concepts and increasing the user's emotional engagement. Several studies highlight how carefully designed stories or scenarios improve users' understanding and motivation [36], [37], [41], [46], [47]. Regarding simulated environments with clear and realistic visual elements, it was found that they not only facilitate learning but also allow risk-free practices that enhance student confidence.

Another factor, such as immersion and the sense of presence, is a dimension related to the perception of "being present" in the virtual environment [50]. Studies like [32], [46], [47] show that graphic quality, multisensory stimuli, and the use of realistic avatars directly influence immersion and user engagement. Thus, [39] adds that the active manipulation of visual depth and haptic stimuli intensifies the sense of presence and learning effectiveness.

Personalization and adaptability refer to inclusive design that adjusts to users' needs, which was identified as a critical factor. Regarding interfaces, they allow for adjusting difficulty or interaction modes based on the user's experience (such as comfortable positions or guided flow), enhancing engagement and reducing cognitive load [41], [47], and personalization thus contributes to greater focus on educational goals and a more satisfying experience.

The use of eye-tracking technology, as another factor, allows dynamically adapting visual elements and improving accessibility in educational environments. In [35], [39], and [47], it is demonstrated how this technology enables the redesign of interfaces and directs the user's attention to key areas, personalizing the experience based on visual behavior.

Together, the factors identified and described above work in an integrated manner to significantly influence how the user perceives, engages, and learns within immersive educational virtual reality environments.

RQ2: How do metrics obtained through eye tracking contribute to the design and evaluation of interfaces in virtual reality environments?

Eye tracking is presented as a key tool for understanding how users perceive, process, and interact with visual information. In the 22 studies reviewed, it was found that the use of visual metrics allowed for optimizing the organization of interfaces, evaluating cognitive load, improving accessibility, and dynamically personalizing the experience based on user behavior.

Among the most commonly used metrics were fixations, visual trajectories, saccadic movements, pupillometry, blink rate, and visual response time. These metrics were applied in various contexts for different purposes. The following describes these metrics and their relationship or interpretation of the aspects measured by them:

- In [28], [29], [33], fixations and gaze trajectories were used to identify navigation patterns and points of interest in urban and natural environments, optimizing the placement of key elements in the interface.
- In [30], [34], [35], [36], fixations were used to evaluate the understanding of textual content, while in [37] and [43], areas of higher visual concentration were identified to redesign panels and optimize access to information.
- In [38], [40], [45], pupillometry and fixation duration were applied to measure cognitive load, adjusting task complexity in real time and developing machine learning models to predict user experience.
- In [39], [42], saccadic movements were analyzed as an indicator of efficiency in navigation and spatial accuracy, with fast saccades being associated with smooth exploration and intuitive navigation, while erratic movements reflected greater difficulty in interaction.
- Finally, in [33], [45], [47], heatmaps and blink rates were used to detect visual fatigue, identifying ignored elements and areas of cognitive overload, which allowed for redesigning the visual layout and simplifying navigation.

From this, it is concluded that the metrics provided by eye-tracking technology not only allow for evaluating user performance in specific tasks but also provide objective data to redesign more accessible, adaptive, and user-centered immersive interfaces.

RQ3: What qualitative and quantitative evaluation methods are used to measure user experience in immersive virtual reality environments, and what is their impact on the accuracy of the results?

Based on the analysis of the reviewed studies, it was identified that the evaluation of user experience (UX) in immersive virtual reality environments combines quantitative and qualitative methods to achieve a comprehensive understanding of the interaction between the user and the virtual environment. These approaches complement each other, balancing subjective perception with objective data that allow for evaluating aspects such as usability, immersion, and the effectiveness of the environment.

1. **Quantitative Methods:** Among the most commonly used tools in quantitative measurement, eye tracking stands out, employed in the majority of studies. It allows for recording visual metrics such as fixations, gaze trajectories, pupillometry, saccadic movements, blink rate, and visual response time. These metrics were applied for various purposes:
 - **Fixations and gaze trajectories:** In works such as [35], [36], [38], [40], [41], [42], [43], [44], these metrics allowed for identifying areas of visual interest and reorganizing interface elements to facilitate access and improve navigation.
 - **Pupillometry:** In [28], [30], [37], [38], [40], [42], [43], pupil diameter was used as an indicator of cognitive load during complex tasks or critical events, adjusting the presentation of information based on mental effort.
 - **Blink rate:** Works such as [30], [40], [43], [44] employed this metric to evaluate visual fatigue during navigation, identifying that certain locomotion methods were less cognitively demanding.
 - **Physiological metrics:** In [34], [41], [42], [46], [47], [48], responses such as heart rate, brain activity (EEG), and skin conductance were analyzed to measure stress, emotion, and cognitive overload.
 - **Performance data:** In [29], [39], [45], performance was evaluated through response time, task accuracy, and navigation efficiency.
2. **Qualitative Methods:** Qualitative evaluation, on the other hand, focused on understanding the user's subjective perception, primarily using interviews, surveys, direct observation, and standardized questionnaires.
 - **Questionnaires and subjective instruments:** Studies such as [28], [29], [34], [36], [38], [39], [40], [42], [46] used questionnaires like QUESI or ad hoc scales to measure perceived usability, immersion, and presence.

- **Behavior observation:** [31], [32], [39], [40], [41], [42] used direct observation to detect unanticipated interaction patterns, signs of discomfort, concentration levels, and fluidity in navigation.

From this, it is concluded that the identified methods allowed for the integration of both objective and subjective indicators, thus optimizing the evaluation of user experience from multiple dimensions, including visual, cognitive, and emotional aspects.

RQ4: What are the limitations and technical challenges of using eye tracking technologies in virtual reality environments?

The studies analyzed to answer this question highlight a series of technical limitations and methodological challenges in the use of eye tracking in immersive virtual reality environments. These challenges were grouped into five (5) dimensions: technological dependency, accuracy and calibration, fatigue and cybersickness, user prior experience, and naturalness of the environment.

- 1. Technological or specialized hardware dependency:** Most studies require high-end devices such as the HTC Vive Pro Eye, Varjo, or FOVE, which represent a high cost and limit the scalability of research. Other authors propose alternative solutions, such as [30], where eye tracking was integrated into an Oculus Quest using a 3D-printed mount, and in [33], a desktop eye tracker with a conventional monitor was used, which facilitated calibration but reduced immersion.
- 2. Calibration and accuracy issues:** Variations in posture, head movements, and blinking can introduce noise into the visual data, as highlighted in [29], [37], [44], [47], which emphasize the need for frequent calibrations and the use of post-processing filters to obtain valid data. In [31] and [37], it is warned that abrupt movements or adjustments to the headset can compromise the quality of the recorded information.
- 3. Physical and visual fatigue:** Prolonged use of heavy headsets or those with generic straps can cause discomfort or even pain, affecting session duration [30], [32], [34]. Additionally, symptoms of cybersickness are reported in intense immersive environments. For [31], [34], [36], [37], visual fatigue is associated with poorly designed radial menus, while other works, such as [38], focus on data analysis rather than user comfort.
- 4. Learning curve and prior experience:** Many participants had no prior experience with virtual reality, which introduced several issues: atypical

explorations due to novelty effects [34], difficulties in navigation or interaction through gaze [34], [44], and increased susceptibility to motion sickness [36], [37], [47]. These aspects can affect the validity of the results and require progressive adaptation protocols.

RQ5: How can immersive virtual reality environments be optimized to reduce the incidence of cybersickness and other physical issues?

Negative effects during the immersive experience, such as visual fatigue, cybersickness, cognitive overload, or physical discomfort, are addressed in various studies through mitigation strategies focused on ergonomics, personalization, progressive design, and adaptive monitoring.

- 1. Dynamic adaptation of the field of view (FoV):** One of the most prominent strategies was modifying the field of view to reduce excessive visual stimulation. Studies such as those by [28], [29], [36], [49] propose incorporating no-interaction zones and movement restriction mechanisms to decrease sensory load. For example, [28] introduces a “central zone” that keeps the FoV stable when the user focuses their gaze, facilitating visual rest.
- 2. Ergonomic design of hardware and scheduled breaks:** The physical suitability of the VR headset and peripherals is essential to ensure user comfort. [31], [32], [37], [45], [46] emphasize the need for lighter devices, adjustable straps, and limited usage times. [31] recommends including periodic breaks in prolonged sessions, while [32] highlights that reducing external peripherals improves overall comfort.
- 3. Reduction of cognitive load:** The design of simple interfaces and low-demand tasks helps prevent user mental saturation. Several studies agree on this point, such as [30], [34], [35], [36], [39], which propose moderating the use of text, employing appropriate contrasts, and simplifying menus. In this regard, [30] recommends legible fonts and optimal visual distances, while [34] suggests replacing radial menus with static panels to reduce visual effort.
- 4. Gradual introduction of immersive environments:** Several authors recommend starting with simple experiences that progressively increase in complexity, allowing the user to adapt to the technology. [28], [31], [41], [46], [49] agree on the effectiveness of this approach. In particular, [41] shows that starting in low-interaction environments improves the experience for novice users.

5. **Postural ergonomics:** It was found that physical posture during VR use has a direct impact on comfort and the sense of control. [41] advocates for the use of seated positions to reduce muscle strain. [32] and [36] emphasize the need for rest areas and lightweight equipment design to extend the experience without fatigue.
6. **Real-time adaptive monitoring:** Some studies implement continuous monitoring systems that allow for dynamically adjusting the experience based on the user's visual load. [35], [43], and [48] integrate heatmaps or exploration indexes to detect overload and reconfigure the interface. For example, [48] proposes a visual convergence index that automatically adjusts the narrative when erratic exploration patterns are detected.

The strategies found show a consensus on the importance of user-centered design as a means to minimize adverse effects in immersive experiences. The combination of ergonomic elements, visual calibration, gradual interaction, and real-time adaptability is presented as key to enhancing the overall experience and reducing usability barriers.

RQ6: What models or frameworks have been developed to evaluate user experience in virtual reality environments?

Although most of the studies do not formally present validated "frameworks" or models, much of the reviewed literature proposes structured methodologies for evaluating user experience in virtual reality environments, combining quantitative and qualitative techniques with the use of technologies such as eye tracking and physiological measurement, which were grouped as follows:

1. **Models based on dynamic adjustment:** A group of studies focuses on systems that adapt the immersive experience in real time based on visual or physiological data. For example, in [35], they present a system that combines real-time eye tracking, heatmaps, and points of interest in Unity to redirect the user's attention. Similarly, [40] proposes a dynamic stereoscopic adjustment model with MLP neural networks to prevent cybersickness, automatically modifying depth and camera separation parameters based on visual behavior.
2. **Frameworks applied to specific contexts:** Some works develop methodological frameworks for specific domains. [37] designs a training ecosystem for maritime safety that integrates high-precision hardware (Varjo

VR-2 Pro), gaze analysis, and progressive risk scenarios. Meanwhile, [38] develops a prediction model based on Random Forest to assess user satisfaction in locomotion tasks, using metrics such as fixations, saccades, and gaze trajectories.

- 3. Integrated multidimensional approaches:** Other studies propose models that integrate various evaluation methods. In [41], a multimodal approach is presented in the educational environment MolGenVR, where the following are combined: (a) physiological sensors (EEG, GSR) to monitor emotional response and stress, (b) usability and immersion questionnaires, and (c) eye tracking to observe conceptual understanding. This structure, designed for natural sciences, is adaptable to various educational contexts.
- 4. Models oriented to architectural and emotional design:** In the field of space design, [36] and [42] develop pre-evaluation frameworks for architecture that combine eye tracking, emotional valence/activation models, and spatial analysis. Although aimed at architectural environments, their methodologies are useful for evaluating VR interfaces based on emotional response, cognitive load, and spatial perception.
- 5. Group and cinematic models:** In [48], the Visual Attention Convergence Index is introduced, a model that quantifies collective attention in 360° scenes. Its purpose is to measure whether visual narratives effectively direct group attention. Although initially applied to cinematic environments, this index can be extrapolated to educational or training simulations with multiple users.
- 6. Modular toolkits for interactive VR:** A representative example is LoopAR [49], a Unity toolkit designed to study interaction during critical events in autonomous vehicles, which integrates eye tracking, simulated events, and visual analysis tools. Despite its focus on driving, its modular structure and integration capabilities make it applicable to other VR experiments that require attention and response evaluation in dynamic scenarios.

Based on the above, a clear trend toward the structuring of hybrid methodologies that combine visual analysis, physiological feedback, and subjective evaluation can be observed. This will allow for a more comprehensive evaluation of the user experience and lead to real-time adaptive systems that personalize the immersive experience based on user behavior.

To overcome the deficiencies and limitations identified in the evaluation of user experience in immersive virtual reality educational environments, it is essential

to implement a comprehensive strategy. First, it is crucial to mitigate visual fatigue and cybersickness by dynamically adjusting the field of view, limiting session durations with breaks, and promoting seated postures. Furthermore, the accuracy of eye tracking requires more automated calibrations and post-processing filters to reduce noise. For the learning curve of novice users, a gradual introduction to scenarios and the use of adaptive interfaces are recommended. Finally, it is vital to enhance the reliability and generalizability of research by incorporating larger and more diverse samples, developing more complex virtual scenarios for extended use, and integrating eye tracking with other physiological sensors and manual recognition, along with advanced ocular metrics.

CONCLUSIONS

The systematic review conducted allowed for the identification, classification, and analysis of the current state of research related to the evaluation of user experience in immersive educational virtual reality environments using eye-tracking techniques. It serves as a foundation for future research aimed at developing robust and comparable tools that can improve the quality and effectiveness of VR-based educational environments.

The results show that, while there has been significant progress in the application of these technologies, important methodological challenges persist. Among them, the lack of standardized evaluation frameworks, the dispersion in the approaches used, and the lack of integration between visual metrics and structured educational contexts stand out. Additionally, an emerging trend is observed toward combining eye tracking with other techniques, such as physiological analysis or machine learning, which opens new possibilities to enrich UX evaluation.

Additionally, there is increasing adoption of eye tracking as a non-invasive quantitative tool to evaluate key dimensions such as visual attention, cognitive load, and user interaction.

On the other hand, this study allowed for the identification of gaps in the literature, such as the low number of studies with large samples and diverse user profiles, as well as limited attention to variables such as cybersickness or the prolonged duration of immersive experiences. These aspects are critical for the development of more accessible, effective, and user-adapted environments.

Finally, it is concluded that it is necessary to move toward the consolidation of methodological frameworks that integrate both technical and pedagogical criteria, considering UX as a central component in the design and evaluation of immersive

educational experiences. This work provides a solid foundation for future research aimed at developing more robust and comparable tools that can improve the quality and effectiveness of virtual reality-based educational environments.

REFERENCES

- [1] Y. B. Guzmán, “Tecnologías de información y comunicación en la educación superior,” *Horizontes Revista de Investigación en Ciencias de la Educación*, vol. 7, no. 29, pp. 1564–1579, Apr. 2023, doi: <https://doi.org/10.33996/revistahorizontes.v7i29.613>.
- [2] J. K. Toala-Palma, J. L. Arteaga-Mera, J. M. Quintana-Loor, and M. I. Santana-Vergara, “La realidad virtual como herramienta de innovación educativa,” *EPISTEME KOINONIA*, vol. 3, no. 5, pp. 270–270, Jun. 2020, doi: <https://doi.org/10.35381/e.k.v3i5.835>.
- [3] I. Wohlgenannt, A. Simons, and S. Stieglitz, “Virtual reality,” *Business & Information Systems Engineering*, vol. 62, no. 5, pp. 455–461, 2020, doi: <https://doi.org/10.1007/s12599-020-00658-9>.
- [4] K. Avezova, A. Kozibay, Y. Bayzakova, Z. Zhumagalieva, and M. Tuken, “The use of modern information and communication technologies in the educational process,” *Scientific Herald of Uzhhorod University. Series Physics*, no. 55, pp. 348–350, 2024, doi: <https://doi.org/10.54919/physics/55.2024.34hc5>.
- [5] International Standardization Organization, “ISO 9241-210:2019,” 2019. [Online]. Available: <https://www.iso.org/standard/77520.html>
- [6] B. Esperanza, J. Dayana, G. Tenezaca, E. Mauricio, and E. Briones, “Recursos educativos en los centros educativos ecuatorianos,” *Ciencia Latina Revista Científica Multidisciplinar*, vol. 8, no. 1, pp. 4958–4973, Feb. 2024, doi: https://doi.org/10.37811/cl_rcm.v8i1.9832.
- [7] V. Souza, A. Maciel, L. Nedel, and R. Kopper, “Measuring presence in virtual environments: A survey,” *ACM Computing Surveys*, vol. 54, no. 8, pp. 1–37, Oct. 2021, doi: <https://doi.org/10.1145/3466817>.
- [8] R. da Silva Soares, A. Y. A. Oku, C. da S. F. Barreto, and J. R. Sato, “Exploring the potential of eye tracking on personalized learning and real-time feedback in modern education,” *Progress in Brain Research*, pp. 49–70, 2023, doi: <https://doi.org/10.1016/bs.pbr.2023.09.001>.
- [9] S. Soares, C. Barreto, and J. R. Sato, “Perspectives in eye-tracking technology for applications in education,” *South African Journal of Childhood Education*, vol. 13, no. 1, p. 8, 2023. [Online]. Available: <https://sajce.co.za/index.php/sajce/article/view/1204/2416>

- [10] M. G. Salinas, "Eye tracking, una herramienta complementaria para la evaluación del diseño," *Zincografía*, vol. 7, no. 13, pp. 221–240, Apr. 2023, doi: <https://doi.org/10.32870/zcr.v7i13.203>.
- [11] S. M. Roa-Martínez and S. A. B. G. Vidotti, "Eye tracking and usability in digital informational environments: Theoretical review and evaluation procedure proposal," *Transinformação*, vol. 32, p. e190067, 2020, doi: <https://doi.org/10.1590/1678-9865202032e190067>.
- [12] A. Gorbunovs, "The review on eye tracking technology application in digital learning environments," *Baltic Journal of Modern Computing*, vol. 9, no. 1, pp. 1–24, Jan. 2021, doi: <https://doi.org/10.22364/bjmc.2021.9.1.01>.
- [13] N. Y. González Hernández and R. Victoria-Urbe, "Diseño de experiencia de usuario para la transferencia de conocimientos en entornos de realidad virtual," *I+Diseño*, vol. 18, pp. 83–96, Dec. 2023.
- [14] L. Ramos Achicanoy and F. A. Dulce Mera, "Pedagogical support tools: Integrating digital tools for learning about AC electrical circuits within electronic engineering," *ing. Solidar*, vol. 20, no. 2, pp. 1–22, Oct. 2024, doi: <https://doi.org/10.16925/2357-6014.2024.02.05>.
- [15] S. Andrés and V. Rosada, "VRTBloom: Framework para la creación de actividades de aprendizaje para realidad virtual basadas en el primer nivel de la taxonomía de Bloom," 2022. [Online]. Available: <http://repositorio.unicauca.edu.co:8080/xmlui/handle/123456789/5521>
- [16] R. Wang, R. Lowe, S. Newton, and T. Kocaturk, "Task complexity and learning styles in situated virtual learning environments for construction higher education," *Automation in Construction*, vol. 113, p. 103148, Mar. 2020, doi: <https://doi.org/10.1016/j.autcon.2020.103148>.
- [17] "Marco de referencia para construcción de herramientas de autor de aplicaciones inmersivas para enseñanza en educación superior," GICO, 2017. [Online]. Available: <https://www.unicauca.edu.co/gico/trabajos-dirigidos/marco-de-referencia-para-construcción-de-herramientas-de-autor-de-aplicaciones>
- [18] I. Díaz-Oreiro, G. López, L. Quesada, and L. A. Guerrero, "UX evaluation with standardized questionnaires in ubiquitous computing and ambient intelligence: A systematic literature review," *Advances in Human-Computer Interaction*, vol. 2021, p. 5518722, 2021, doi: <https://doi.org/10.1155/2021/5518722>.
- [19] G. López, I. Díaz-Oreiro, L. Quesada, and K. Ramírez-Benavides, "Translation and validation of the AttrakDiff user experience questionnaire to Spanish," *Lecture Notes in Networks and Systems*, pp. 243–254, Jan. 2023, doi: https://doi.org/10.1007/978-3-031-48306-6_25.

- [20] E. Mitsiou, "Measuring UX: User Experience Questionnaire (UEQ)," *Articles on Everything UX: Research, Testing & Design*, Nov. 15, 2024. [Online]. Available: <https://blog.uxtweak.com/user-experience-questionnaire/>
- [21] M. Minge, M. Thüning, I. Wagner, and C. V. Kuhr, "The meCUE questionnaire: A modular tool for measuring user experience," *Advances in Intelligent Systems and Computing*, pp. 115–128, Jul. 2016, doi: https://doi.org/10.1007/978-3-319-41685-4_11.
- [22] L. Codina, "Revisiones de la literatura y cómo llevarlas a cabo con garantías: systematic reviews y SALSA Framework." [Online]. Available: <https://www.lluiscodina.com/revision-sistemica-salsa-framework/>
- [23] K. Petersen, R. Feldt, S. Mujtaba, and M. Mattsson, "Systematic mapping studies in software engineering," *Electronic Workshops in Computing*, Jun. 2008, doi: <https://doi.org/10.14236/ewic/ease2008.8>.
- [24] M. Petticrew and H. Roberts, *Systematic Reviews in the Social Sciences: A Practical Guide*, pp. 1–336, Jan. 2008, doi: <https://doi.org/10.1002/9780470754887>.
- [25] J. Brooke, "SUS: A 'quick and dirty' usability scale," *CRC Press eBooks*, vol. 189, no. 194, pp. 4–7, Jun. 1996, doi: <https://doi.org/10.1201/9781498710411-35>
- [26] H. B. Santoso, M. Schrepp, L. M. Hasani, R. Fitriansyah, and A. Setyanto, "The use of User Experience Questionnaire Plus (UEQ+) for cross-cultural UX research: Evaluating Zoom and Learn Quran Tajwid as online learning tools," *Heliyon*, vol. 8, no. 11, pp. e11748–e11748, Nov. 2022, doi: <https://doi.org/10.1016/j.heliyon.2022.e11748>.
- [27] NASA Ames Research Center, "TLX @ NASA Ames - Home," 2020. [Online]. Available: <https://humansystems.arc.nasa.gov/groups/tlx/>
- [28] H. C. Kim, S. Jin, S. Jo, and J. H. Lee, "A naturalistic viewing paradigm using 360° panoramic video clips and real-time field-of-view changes with eye-gaze tracking," *NeuroImage*, vol. 216, p. 116617, 2020, doi: <https://doi.org/10.1016/j.neuroimage.2020.116617>.
- [29] S. Zhao and S. Cheng, "Adaptive navigation assistance based on eye movement features in virtual reality," *Virtual Reality and Intelligent Hardware*, vol. 5, no. 3, pp. 232–248, 2023, doi: <https://doi.org/10.1016/j.vrih.2022.07.003>.
- [30] T. Kojic, M. Vergari, S. Möller, and J. N. Voigt-Antons, "Assessing user experience of text readability with eye tracking in virtual reality," *Springer*, pp. 199–211, 2022, doi: https://doi.org/10.1007/978-3-031-05939-1_13.

- [31] M. T. Mendoza-Medialdea et al., “Attentional bias modification training in virtual reality: Evaluation of user experience,” *Applied Sciences*, vol. 14, no. 1, p. 222, 2024, doi: <https://doi.org/10.3390/app14010222>.
- [32] A. Visconti, D. Calandra, and F. Lamberti, “Comparing technologies for conveying emotions through realistic avatars in virtual reality-based metaverse experiences,” *Computer Animation and Virtual Worlds*, vol. 34, no. 3–4, p. e2188, 2023, doi: <https://doi.org/10.1002/cav.2188>.
- [33] M. Ni, N. Ni, H. Liu, L. Jiang, and W. Mo, “Design optimization for the coating of machine tools based on eye-tracking experiments and virtual reality technology,” *Applied Sciences*, vol. 12, no. 20, p. 10640, 2022, doi: <https://doi.org/10.3390/app122010640>.
- [34] M. Brabec, T. Benda, P. Benda, P. Šimek, M. Havránek, and V. Lohr, “Developing a functional user interface for VR simulations within agricultural equipment contexts,” *Agris On-line Papers in Economics and Informatics*, vol. 16, no. 1, pp. 15–22, 2024, doi: <https://doi.org/10.7160/aol.2024.160102>.
- [35] S. H. Nam and J. I. Choi, “Development of a user evaluation system in virtual reality based on eye-tracking technology,” *Multimedia Tools and Applications*, vol. 82, no. 14, pp. 21117–21130, 2023, doi: <https://doi.org/10.1007/s11042-023-14583-y>.
- [36] N. Kim and H. Lee, “Evaluating visual perception by tracking eye movement in architectural space during virtual reality experiences,” *Springer*, pp. 302–308, 2020, doi: https://doi.org/10.1007/978-3-030-44267-5_45.
- [37] M. Luimula et al., “Eye tracking in maritime immersive safe oceans technology,” *IEEE*, pp. 245–250, Sep. 2020, doi: <https://doi.org/10.1109/CogInfoCom50765.2020.9237854>.
- [38] H. Gao and E. Kasneci, “Eye-tracking-based prediction of user experience in VR locomotion using machine learning,” *Computer Graphics Forum*, vol. 41, no. 7, pp. 589–599, 2022, doi: <https://doi.org/10.1111/cgf.14703>.
- [39] C. Zhang, T. Chen, E. Shaffer, and E. Soltanaghaj, “FocusFlow: 3D gaze-depth interaction in virtual reality leveraging active visual depth manipulation,” *ACM*, pp. 1–18, 2024, doi: <https://doi.org/10.1145/3613904.3642589>.
- [40] B. Terzioğlu, U. Celikcan, and T. K. Capin, “Gaze-contingent adaptation of VR stereo parameters for cybersickness prevention,” *The Visual Computer*, vol. 40, no. 7, pp. 5017–5028, 2024, doi: <https://doi.org/10.1007/s00371-024-03505-0>.

- [41] M. Lui, R. McEwen, and M. Mullally, "Immersive virtual reality for supporting complex scientific knowledge: Augmenting our understanding with physiological monitoring," *British Journal of Educational Technology*, vol. 51, no. 6, pp. 2180–2198, 2020, doi: <https://doi.org/10.1111/bjet.13022>.
- [42] W. Pei, X. Guo, and T. Lo, "Pre-evaluation method of the experiential architecture based on multidimensional physiological perception," *Journal of Asian Architecture and Building Engineering*, vol. 22, no. 3, pp. 1170–1194, 2023, doi: <https://doi.org/10.1080/13467581.2022.2074019>.
- [43] F. Li, C. H. Lee, S. Feng, A. Trappey, and F. Gilani, "Prospective on eye-tracking-based studies in immersive virtual reality," *IEEE*, pp. 861–866, 2021, doi: <https://doi.org/10.1109/CSCWD49262.2021.9437692>.
- [44] H. Gao, L. Frommelt, and E. Kasneci, "The evaluation of gait-free locomotion methods with eye movement in virtual reality," *IEEE*, pp. 530–535, 2022, doi: <https://doi.org/10.1109/ISMAR-Adjunct57072.2022.00112>.
- [45] E. Giatzoglou et al., "The Trail Making Test in Virtual Reality (TMT-VR): The effects of interaction modes and gaming skills on cognitive performance of young adults," *Applied Sciences*, vol. 14, no. 21, p. 10010, 2024, doi: <https://doi.org/10.3390/app142110010>.
- [46] G. Pochwatko et al., "Transdisciplinary approach to virtual narratives – Towards reliable measurement methods," *Springer*, pp. 202–212, 2023, doi: https://doi.org/10.1007/978-3-031-37649-8_20.
- [47] Y. H. Liu et al., "User engagement with driving simulators: An analysis of physiological signals," *Springer*, pp. 130–149, 2020, doi: https://doi.org/10.1007/978-3-030-59987-4_10.
- [48] P. Kobylinski and G. Pochwatko, "Visual attention convergence index for virtual reality experiences," *Springer*, pp. 310–316, 2020, doi: https://doi.org/10.1007/978-3-030-25629-6_48.
- [49] F. N. Nezami et al., "Westdrive x loopAR: An open-access virtual reality project in Unity for evaluating user interaction methods during takeover requests," *Sensors*, vol. 21, no. 5, pp. 1–13, 2021, doi: <https://doi.org/10.3390/s21051879>.
- [50] C. Coelho, J. Tichon, T. J. Hine, G. Wallis, and G. Riva, "Media presence and inner presence: The sense of presence in virtual reality technologies," in *From Communication to Presence: Cognition, Emotions and Culture Towards the Ultimate Communicative Experience*, pp. 25–45, Jan. 2006.