A Usability and User Experience Evaluation Technology for Touchable Holographic Solutions

Thiago Prado de Campos[1,3], **Eduardo Filgueiras Damasceno**[2], **Natasha M. C. Valentim**[3]

[1]Federal Technological University of Paraná (UTFPR)
731 João Miguel Caram Avenue - Postal Code 86036-700 – Londrina, PR -– Brazil

[2]Federal Technological University of Paraná (UTFPR) – Cornélio Procópio, PR – Brazil

[3]Federal University of Paraná (UFPR) – Curitiba, PR – Brazil

thiagocampos@utfpr.edu.br, damasceno@utfpr.edu.br, natasha@inf.ufpr.br

Abstract. Introduction*: Touchable Holographic Solutions (THS) present novel challenges for evaluating usability and user experience (UX), particularly in relation to immersion and presence. Traditional instruments may not fully capture the specific aspects involved in interacting with holographic content.* ***Objective:*** *This work aims to present UUXE-ToH, a questionnaire specifically designed to evaluate usability and UX in THS contexts.* ***Methodology or Steps****: The questionnaire was developed through a multi-step process that included systematic mapping studies, exploratory search, expert validation, and studies with end users. The final version of the instrument comprises 56 items grouped into 19 aspects.* ***Results:*** *Empirical studies indicate that UUXE-ToH is a valid and reliable instrument. It identifies more usability and UX issues compared to existing instruments and is also rated more positively in terms of ease of use and acceptance.*

Keywords *Touchable Holography, Usability, User eXperience (UX), Evaluation*

1. Introduction

Touchable Holographic Solutions (THSs) represent a new interaction paradigm in Augmented Reality (AR) and Mixed Reality (MR) environments, enabling users to manipulate virtual objects through mid-air gestures without relying on physical interfaces such as screens or handheld devices [Hoshi et al. 2009, Sinlapanuntakul et al. 2022]. This type of interaction, once confined to science fiction, has become increasingly feasible due to advances in wearable devices and hand-tracking sensors embedded in smart glasses and MR headsets. THS eliminates traditional input devices and physical touch surfaces, offering more natural, spatial, and embodied ways to manipulate 3D content. THS have shown potential in areas such as training, education, and entertainment, where intuitive and immersive interaction enhances learning, engagement, and task performance. However, evaluating the quality of such systems remains a challenge, as it requires not only the assessment of traditional usability criteria but also subjective aspects of User Experience (UX), including presence and emotional responses, attributes that are particularly significant in immersive environments.

This research aimed to design, validate, and apply a dedicated evaluation technology for THSs, materialized as a questionnaire. An evidence-based empirical approach was adopted, structured into three phases: (i) investigation and theoretical

foundation, conducted through a Systematic Mapping Study (SMS) and exploratory search; (ii) proposal and initial validation of the evaluation technology; and (iii) empirical studies with expert and end-users, applying statistical tests for validity, reliability, performance, and acceptability. The outcome is the Usability and User eXperience Evaluation in Touchable Holography (UUXE-ToH) questionnaire, which integrates usability and UX criteria into a single instrument and has been tested in multiple studies focused on its applicability, validity, and ability to identify interaction issues. This contribution addresses gaps in the literature and provides an accessible and comprehensive tool for researchers and practitioners engaged in evaluating emerging immersive technologies.

The remainder of this article is organized as follows. Section 2 presents the research problem and motivation for this study. Section 3 describes the proposed solution, including the rationale and structure of the UUXE-ToH questionnaire. Section 4 explains the methods adopted across all stages of the research. Section 5 shows other works with similar goals. Section 6 synthesizes the main findings, including qualitative and quantitative analyses. Section 7 presents some limitations in the research and results interpretations. Section 8 outlines the ethical considerations. Section 9 shows publications and other relevant products from the research. Section 10 discusses the contributions of the study to the Human-Computer Interaction (HCI) field. Finally, Section 11 presents the conclusions and directions for future work.

2. Research Problem and Goals

A defining feature of THS is the sensory and perceptual experience they generate. Unlike conventional systems, THS merges physical and virtual spaces, requiring the user to perceive virtual objects as coexisting with the real environment. This hybrid interaction depends strongly on two critical experiential dimensions: **immersion** and **presence**. Immersion refers to the system's ability to envelop the user through multisensory stimuli, while presence relates to the psychological sensation of "being there" in the augmented or mixed space [Slater 2009, Skarbez et al. 2021, Skarbez et al. 2022]. These aspects are central to how users interpret and emotionally respond to holographic content.

However, evaluating such experiences poses serious challenges. THS typically lack physical feedback mechanisms (e.g., haptics), making interaction dependent on visual and auditory cues. The spatial nature of the interface and gesture-based input introduces variability in interpretation and cognitive load. Furthermore, immersive environments can induce effects such as motion sickness or fatigue, which impact UX and require careful assessment. Evaluating these systems requires tools capable of capturing not only pragmatic aspects such as efficiency and effectiveness but also hedonic and emotional dimensions, including aesthetics, stimulation, satisfaction, and emotional response [Hassenzahl 2008, Campos et al. 2024b].

Traditional instruments such as the System Usability Scale (SUS) [Brooke 1996] and the User Experience Questionnaire (UEQ) [Laugwitz et al. 2008] are widely used in usability and UX evaluations. However, these tools were developed for conventional screen-based or desktop systems and are not well-suited to capture the complexity of interaction in immersive environments like THS. They often fail to address key aspects such as spatial awareness, user embodiment, or the feeling of virtual object "realness." As

a workaround, multiple generic instruments are frequently combined to assess THS, but this leads to overlapping constructs, redundancy, user fatigue, and increased complexity in data interpretation [Campos et al. 2023, Alexandrovsky et al. 2021].

This scenario highlights a major gap: the lack of a dedicated, validated, and comprehensive evaluation technology (ET) capable of **simultaneously and integratively assessing usability and UX in THS**. Without appropriate tools, essential user feedback is lost or misinterpreted, potentially compromising the design, accessibility, and adoption of these emerging technologies. As a consequence, developers and researchers may overlook usability flaws or UX frictions that negatively affect learning, engagement, or satisfaction.

The goal of this research was to propose, develop, and validate an evaluation technology tailored to the specificities of THS. The instrument should allow a unified assessment of both usability and UX dimensions, incorporating factors relevant to immersive interaction, such as immersion, presence, embodiment, comfort, and emotions. To achieve this, the research followed an iterative, multi-method approach involving systematic literature analysis, expert evaluation, user-centered testing, and statistical validation. This led to the development of the UUXE-ToH questionnaire, an evaluation tool designed to meet the growing demand for structured and context-sensitive assessment of touchable holographic experiences.

The central research question guiding this work was:

How can we evaluate touchable holographic solutions considering their unique interaction characteristics, while simultaneously addressing usability and user experience in an integrated and context-aware manner?

3. Produced Solution

To address the identified lack of integrated and context-sensitive evaluation tools for THS, this research resulted in the development of a set of practical solutions and artifacts.

One of the core solutions was the formal definition of a set of usability and UX aspects applicable to THS (Figure 1) [Prado De Campos et al. 2024]. This set includes both pragmatic dimensions (such as effectiveness, efficiency, learnability, controllability, and error prevention) and hedonic dimensions (such as stimulation, pleasure, aesthetics, and emotional response). Also was included immersion and presence, as special dimensions related to THS. These aspects were structured to be observable, measurable, and useful, forming the conceptual foundation for the other artifacts developed in the project.

Supporting this conceptual model, two systematic mapping studies were conducted and organized into technical reports [Campos et al. 2023, Campos et al. 2024a]. These documents classify evaluation technologies and THS applications, based on different research questions and criteria. The reports offer detailed mappings of the literature, including taxonomy of gesture types, feedback modalities, display technologies, and the evaluation methods used. These artifacts support reproducibility, transparency, and provide a referential base for other researchers and designers working in the same domain.

Based on the defined aspects, the central evaluation instrument developed in this research is the **UUXE-ToH questionnaire**. This instrument was produced iteratively and

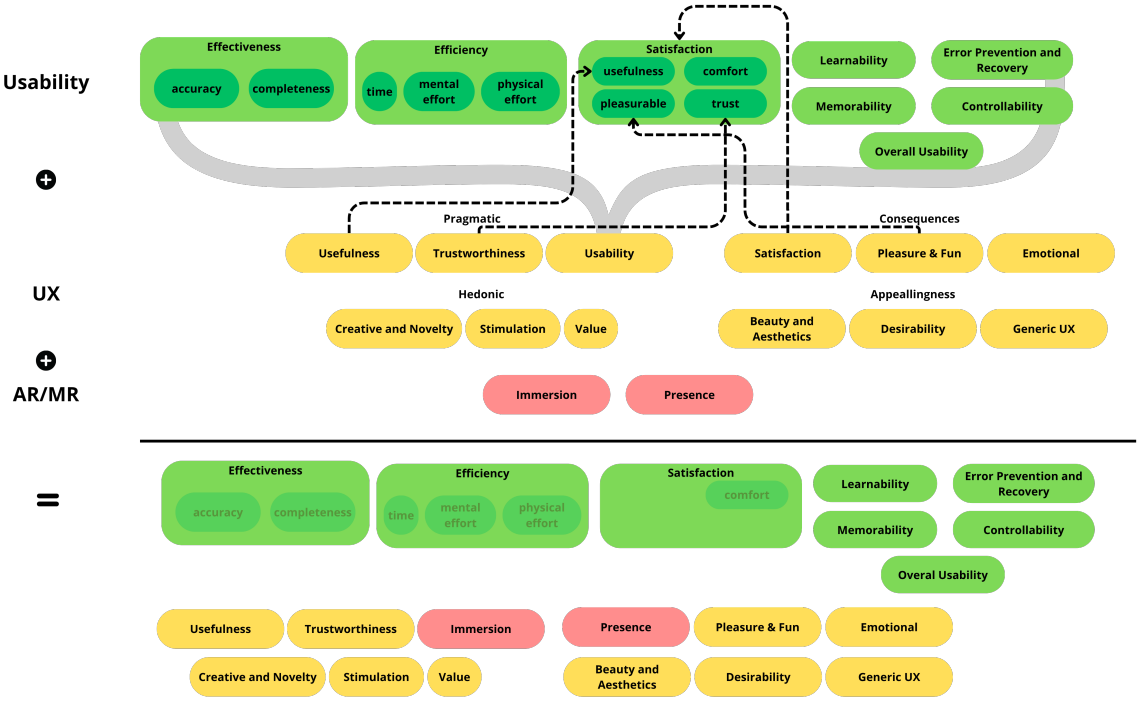

Figura 1. Aspects set for THS. Adapted from [Prado De Campos et al. 2024]

structured across four main versions (v1 to v4), each refined based on expert feedback, user testing, statistical analyses, and comparative studies.

The UUXE-ToH v4 (illustrated in Figure 2 and available online[1]) is composed of two main parts:

- **Part I – Assessment by Aspect:** 50 objective items organized into 19 predefined evaluation aspects, each answered on a 7-point Likert scale. It also includes 6 items using a 7-point semantic differential scale to capture affective responses related to pleasure, fun, and emotions.
- **Part II – Global Feedback:** A global experience rating on a 7-point scale, and four open-ended questions designed to capture additional feedback, perceived difficulties, and suggestions from participants.

Over the course of its development, successive refinements led to important structural adjustments in the set of aspects evaluated. For instance, the construct **Comfort** was separated from **Satisfaction** to better capture both physical and mental comfort during use. The dimension **Stimulation** was decomposed into two distinct experiential aspects: **Interest**, which focuses on user curiosity and attentional engagement, and **Absorption**, which includes engagement and flow-like experiences. The construct **Desirability**, previously considered, was removed due to conceptual overlap and lack of empirical distinction. Additionally, the concept of **Operability** was incorporated into the existing **Controllability** aspect, resulting in a combined dimension labeled **Controllability and Operability**.

These refinements led to the final organization of 19 evaluation aspects in UUXE-ToH v4, presented in Table 1. To support the application and dissemination of the

[1]UUXE-ToH v4 Questionnaire: https://doi.org/10.6084/m9.figshare.28143752.v1

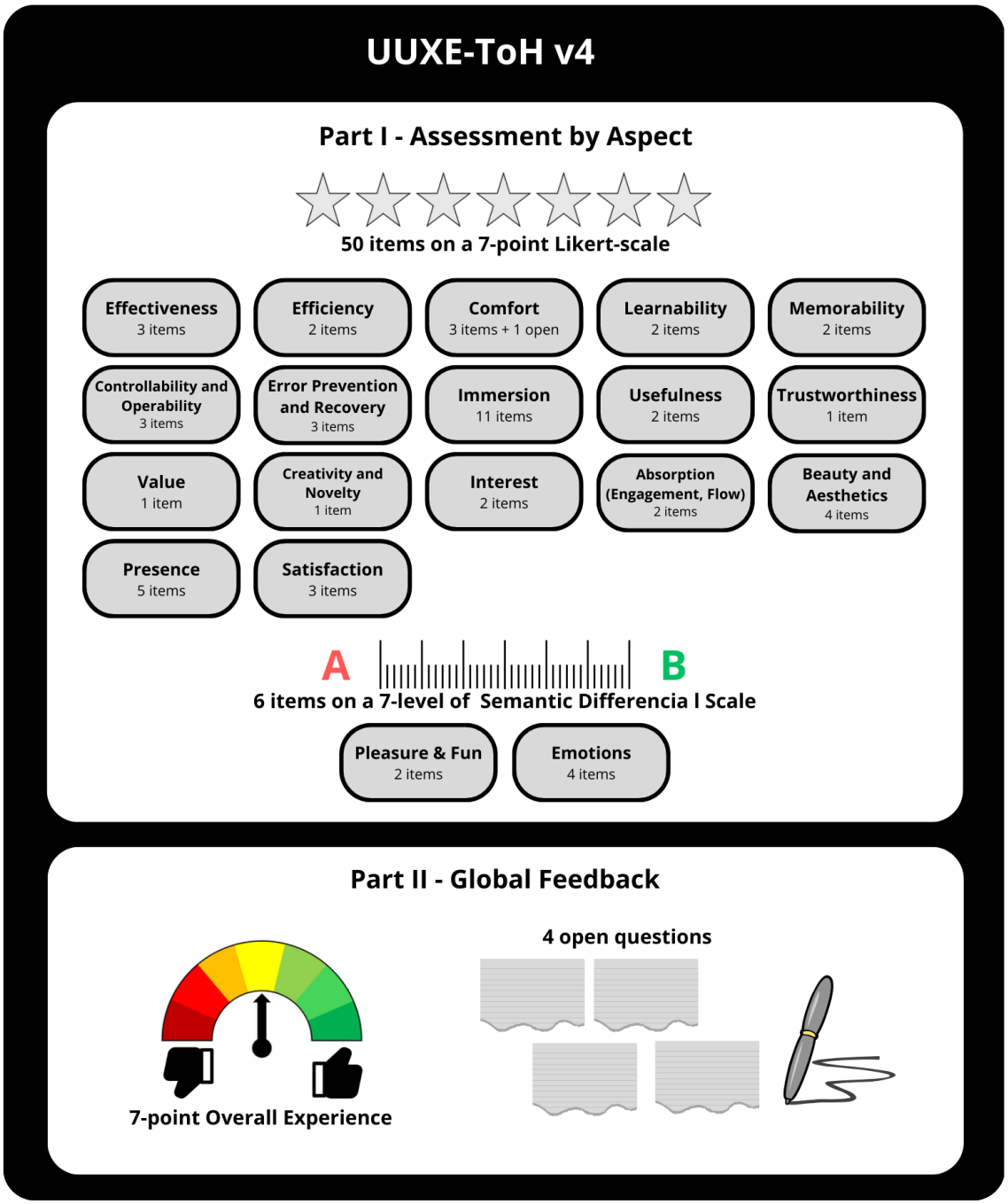

Figura 2. UUXE-ToH v4

questionnaire, a dedicated **website platform** was developed[2]. This platform, available in both English and Brazilian Portuguese, provides:

- Download of the **UUXE-ToH questionnaire in PDF**, in Brazilian Portuguese and English languages;
- A comprehensive **User Manual**, with instructions for use, guidance on customization, and analysis procedures;
- A **web-based form** optimized for tablets and computers, allowing digital application and automatic data recording;
- A results' dashboard with **interactive visual reports**, including median summaries by aspect, radar charts, and heatmaps to aid in interpretation;
- Access to scientific publications and technical documentation about the development, validation, and application of the instrument;
- A contact and support interface for researchers and practitioners using or adapting UUXE-ToH.

Together, these artifacts — evaluation model, systematic mapping reports, UUXE-ToH questionnaire (v1 to v4), usage manual, and the web platform — compose a cohesive set of solutions designed to support structured, repeatable, and context-appropriate evaluations of holographic user experiences.

4. Method

This research adopted an evidence-based approach for the development of an Evaluation Technology (ET), following the methodology proposed by [Shull et al. 2001] and later extended by [Mafra et al. 2006]. This framework was integrated with established guidelines for the construction and validation of psychometric instruments, particularly questionnaires, as outlined by [DeVellis e Thorpe 2022] and [Costa 2021]. Accordingly, the research was structured into three major phases: (1) investigation and theoretical foundation; (2) technology proposition and informal validation; and (3) formal validation and empirical testing.

In **Phase 1**, the goal was to understand the state of the art and identify gaps in usability and UX evaluation of THS. This was achieved through a Systematic Mapping Study (SMS) [Petersen et al. 2015, Kitchenham et al. 2016], complemented by an exploratory study oriented toward knowledge acquisition and synthesis [Marchionini 2006]. These investigations led to the identification of core evaluation aspects, such as immersion and presence, that were either underexplored or not addressed together in existing tools, guiding the definition of latent constructs to be measured.

Phase 2 focused on the initial design of the UUXE-ToH questionnaire, aiming to unify usability and UX constructs in a single instrument tailored for THS contexts. This stage followed best practices in questionnaire development, including construct definition, item generation, expert review, and instrument organization [Boateng et al. 2018, Vieira e Bressan 2022].

Phase 3 comprised a series of empirical studies to validate and refine the instrument. These included content, face, and semantic validations with experts and end-users, as well as statistical analyses to assess internal consistency and dimensionality. This

[2]https://uuxetoh.thiagotpc.com

Tabela 1. Usability and UX Dimensions in UUXE-ToH v4

Effectiveness	relates to users' ability to successfully accomplish specific tasks within a defined context, encompassing accuracy and completeness.
Efficiency	refers to the resources, especially time, required to achieve task goals, reflecting how quickly users can reach their objectives.
Comfort	expresses the extent to which the holographic system avoids causing physical or mental strain, allowing users to interact without discomfort.
Learnability	concerns how easily users can perform basic operations with minimal instruction, focusing on intuitive design and the ease of discovering functionalities.
Memorability	pertains to users' ability to regain proficiency after a long period of not using the system, highlighting the retention of interaction skills.
Controllability and Operability	refers to users' ability to direct the system according to their intentions and interact with it easily. It includes intuitive operation and accessibility, supporting users with temporary or permanent physical or cognitive limitations.
Error Prevention and Recovery	assesses whether the system helps users avoid common mistakes and supports them in effectively recovering from errors when they occur.
Immersion	describes the system's ability to create an engaging and absorbing experience, supported by technical elements (e.g., resolution, field of view) and content quality (e.g., realistic simulation, feedback).
Usefulness	indicates how well the system supports users in performing meaningful tasks, reflecting its practical utility and relevance.
Trustworthiness	concerns users' confidence in the system's reliable behavior, brand reputation, and responsible data handling.
Value	evaluates the added benefit the system provides to users' lives, addressing both explicit needs and unspoken expectations.
Creativity and Novelty	relates to the perceived originality and innovative character of the holographic system.
Interest	refers to the initial curiosity and attraction users feel toward the solution, driven by contextual and personal factors that motivate exploration and engagement.
Absorption	describes a state of focused involvement and loss of time awareness during interaction, reflecting deep engagement and aligning with the concept of Flow.
Beauty and Aesthetics	reflects users' perception of the system's visual and auditory appeal, including aspects like color, form, and harmony.
Presence	indicates whether users felt that virtual elements were truly part of their physical environment, reacting as if those elements were real.
Pleasure and Fun	refers to the enjoyment derived from using the system, especially when the experience exceeds expectations or brings unexpected delight.
Emotions	considers whether the system elicited positive emotional responses or avoided triggering negative ones, covering fundamental or universal emotional reactions.

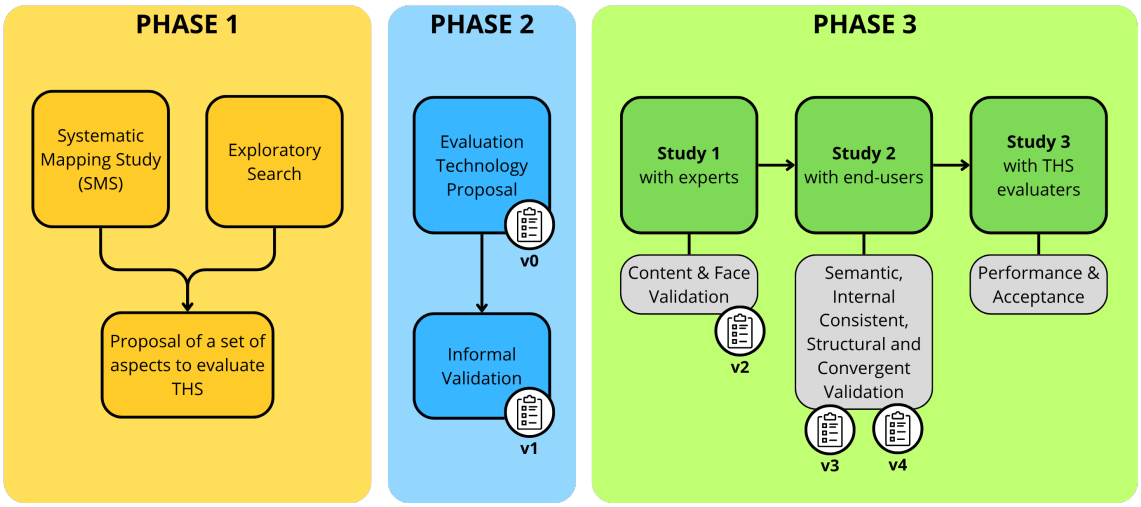

Figura 3. Methodology

phase parallels the feasibility and observational studies proposed by [Shull et al. 2001], adapted to questionnaire development through pilot testing, exploratory factor analysis, and application in real use scenarios.

By articulating both methodological frameworks (the empirical technology evaluation cycle and the psychometric validation process) this research ensured that the proposed instrument was both contextually appropriate for THS and statistically reliable and valid. Figure 3 summarizes this methodological trajectory, which is further detailed in the following sections.

4.1. Phase 1 - Investigation and Theoretical Foundation

To investigate the state of the art and identify gaps in the evaluation of usability and UX in THS, an SMS was conducted following the protocols of [Kitchenham et al. 2016] and [Petersen et al. 2008] and structured according to the Goal-Question-Metrics (GQM) paradigm [Basili et al. 1994]. The SMS aimed to analyze scientific publications to characterize the evaluation technologies used in this context, including the aspects assessed, types of methods applied, and the interaction and presentation modalities of the holographic solutions. A main research question and several subquestions were defined to guide data extraction, covering criteria such as the type and focus of the ET, empirical methods, and the technical characteristics of the solutions studied.

The search strategy applied a PICOC-based search string [Kitchenham e Charters 2007] in the ACM Digital Library, IEEE Xplore, and Elsevier Scopus databases, allowing the inclusion of studies from computing and related fields. The selection process was conducted in two stages (metadata screening and full-text analysis) by multiple researchers, with agreement measured using the Kappa coefficient to ensure reliability. In parallel, an exploratory study was carried out to identify and organize usability and UX aspects based on international standards and widely recognized literature. These aspects were then used to classify those extracted from the SMS, enabling the identification of underrepresented dimensions, such as immersion and presence, and informing the definition of latent constructs for the proposed ET.

4.2. Phase 2 – Technology Proposition and Informal Validation

Based on the aspects identified in the previous phase, the second phase focused on the design of a unified ET capable of assessing both usability and UX in the context of THS. The first design decision was to combine all aspects into a single integrated set, recognizing that usability is largely encompassed by UX. This consolidation resulted in 20 aspects that guided the creation of the evaluation technology. The second decision was to ensure that the proposed technology would be user-centered, applicable from the user's perspective, capable of capturing both pragmatic and hedonic attributes, including emotional responses such as satisfaction and pleasure. A questionnaire format was chosen as the most suitable means to operationalize this evaluation, given its accessibility, versatility, and appropriateness for collecting user feedback.

The development process followed best practices for questionnaire construction. An initial version (v0) was created with 74 closed-ended items and 3 open-ended questions, covering the 20 previously defined aspects. The sentence items were drafted based on the conceptual definitions of each aspect and supplemented by reviewing and adapting items from evaluation technologies identified in the SMS. A 7-point Likert scale was adopted, offering a nuanced range of agreement and disagreement options, along with alternatives for non-applicability (N/A) or uncertainty (NSR). This preliminary version was reviewed in a meeting with two domain experts, whose feedback led to the refinement, addition, or removal of items, resulting in version 1 (v1) of the questionnaire, composed of 67 closed-ended items and the same 3 open-ended questions. This revised version became the foundation for subsequent validation procedures.

4.3. Phase 3 – Formal Validation and Empirical Testing

4.3.1. Study 1 - Validation with experts

Study 1 aimed to perform a content and face validation of the first version of the UUXE-ToH questionnaire (v1) through a structured review with domain experts. Content validation focused on evaluating the relevance, representativeness, and clarity of the questionnaire items in capturing various facets of the intended constructs [DeVellis e Thorpe 2022]. Simultaneously, face validation assessed how well the items were understood and how appropriate they appeared to respondents. Participants were recruited from research groups in usability, HCI, and immersive technologies across Brazil. After an instructional videoconference and access to UUXE-ToH v1, experts were asked to fill out characterization and evaluation forms. The evaluation involved Likert-scale assessments and open-ended feedback about the clarity and relevance of each item. Responses were processed using spreadsheets and R language, while qualitative data (including annotated PDFs and transcripts of follow-up interviews) were analyzed using the open and axial coding phases of Grounded Theory [Corbin e Strauss 2014]. This approach enabled the identification of strengths, limitations, and suggestions for refining the instrument.

4.3.2. Study 2 - Validation with end-users

Study 2 expanded the evaluation of UUXE-ToH (now in version 2) by conducting a more comprehensive validation process, covering semantic, structural, internal consistency,

and convergent validity. A pilot study was initially conducted with a small sample of participants to verify equipment setup, usability of data collection instruments, and adequacy of procedures. The MR puzzle game Cubism (see Figure 4) [Bouwel 2025] served as the interaction scenario, offering a consistent and accessible context for testing. Insights gained from the pilot led to adjustments in logistics (e.g., use of headset extenders for glasses wearers) and the definition of participant inclusion criteria to mitigate cybersickness risks.

Figura 4. Scenes taken from a promotional trailer demonstrating the game Cubism [Bouwel 2025]

Following the pilot, a large-scale study was conducted across five Brazilian universities and cities (Londrina, Cornélio Procópio, Curitiba - PR, Joinville - SC, and Ouro Preto - MG). A total of 260 participants interacted with Cubism using Meta Quest headsets (versions 2, 3, and Pro), followed by completing the UUXE-ToH v2 questionnaire electronically. A subset of participants also completed the SUS and the UEQ to enable comparative analyses. Semantic validation focused on participants' comprehension and perceived clarity, with results showing high agreement levels. Quantitative analysis of objective items used descriptive statistics, while qualitative feedback was analyzed using Grounded Theory coding methods.

Internal consistency was assessed using Cronbach's alpha and McDonald's omega for each construct, ensuring that item sets reliably measured the same latent concept. Analyses were conducted across multiple data subsets (e.g., by device type) and only when the sample size per construct met minimum ratio criteria. The results highlighted which constructs had robust internal consistency and which items required revision.

To examine structural validity, 36 Exploratory Factor Analyses (EFAs) were conducted across different scenarios and data subsets. These EFAs followed best practices for ordinal data (e.g., polychoric correlations, robust extraction methods, and oblique rotations) and were based on parallel analysis to determine factor count. Items were grouped into smaller theoretical clusters to address sample size limitations, and only EFAs with strong fit indices (CFI > 0.95, RMSEA < 0.05) and limited item loss were retained. Discriminant validity was then assessed through Spearman correlations between construct medians, with low correlations confirming the distinctiveness of constructs.

Finally, convergent validity was evaluated by correlating UUXE-ToH v2 scores with SUS and UEQ metrics. Expected relationships (e.g., usability constructs correlating with SUS scores; hedonic constructs correlating with UEQ aspects such as Attractiveness or Novelty) were confirmed through statistically significant Spearman correlations.

4.3.3. Study 3 - Validation with evaluators

Study 3 investigated the performance and acceptance of UUXE-ToH v4 in comparison with a combined evaluation instrument (USE + Slater-Usoh-Steed + UEQ) during a hands-on session at the IHC 2024 conference [Campos et al. 2025a, Campos et al. 2025c, Campos et al. 2024c, Campos et al. 2025b]. Participants used either UUXE-ToH v4 or the combined questionnaires to evaluate Cubism, followed by usability inspections and a final acceptance form. Participants were divided into two groups: Group A used UUXE-ToH v4, while Group B used the combined toolset. Each group reported usability issues and completed a Techonolgy Acceptance Model (TAM) form assessing constructs such as perceived usefulness (PU), perceived ease of use (PEOU), and behavioral intention (BI).

This structured and iterative methodology ensured that the UUXE-ToH questionnaire evolved through a cycle of progressive refinement grounded in both theory and empirical evidence. By integrating expert review, user-centered validation, statistical analysis, and comparative testing, the resulting instrument is a robust, comprehensive, and domain-specific tool for evaluating usability and UX in THS.

5. Related Works

Various instruments have been developed to assess usability and UX in interactive systems. Among the most widely used are the System Usability Scale (SUS), the User Experience Questionnaire (UEQ), the USE questionnaire, and the Presence Questionnaire (PQ). Although these tools present strong psychometric properties and have been validated in diverse contexts, they were not designed for the specific demands of immersive environments like THS.

The **SUS** [Brooke 1996], one of the most established instruments, has undergone multiple validation studies. While earlier analyses proposed a two-factor structure (usability and learnability) [Lewis e Sauro 2009], later studies with larger datasets reinforced its use as a unidimensional tool [Lewis e Sauro 2017]. Despite its broad applicability, SUS does not offer sufficient granularity to capture the hedonic and immersive qualities central to THS experiences.

The **USE** [Gao et al. 2018] questionnaire demonstrated high internal consistency (Cronbach's alpha = 0.98) and significant convergent validity with the SUS. However, factor analysis revealed four factors that did not align with the original model, indicating the need for further refinement. Additionally, there was no reported content or face validation with experts, nor semantic validation with end-users.

The **UEQ** [Laugwitz et al. 2008] was validated through two usability studies involving psychometric analysis and comparisons with the AttrakDiff2 [Hassenzahl et al. 2003]. These studies confirmed expected correlations between constructs, supporting its initial validity. However, little is reported regarding adaptation or refinement based on end-user feedback, limiting its responsiveness to specific interaction contexts such as mid-air holography.

The **Presence Questionnaire (PQ)** [Witmer e Singer 1998] has high internal consistency and is well-established for measuring presence in virtual environments. However, it lacks detailed documentation on content, face, or semantic validation, which are essential when interpreting user perceptions in hybrid physical-digital spaces.

In contrast, the **UUXE-ToH** questionnaire was designed following a multi-layered validation process, including content and face validation with domain experts, semantic validation with end-users, exploratory factor analysis, and convergent validation through comparisons with SUS and UEQ. While prior instruments have proven reliability and utility in traditional systems, they fall short when applied to the complex, embodied, and perceptual nature of holographic interaction. UUXE-ToH stands out by addressing this gap with a structured and iterative development approach that prioritized both statistical robustness and user interpretability.

6. Results and Discussion

6.1. From Initial and Extended SMS

Both SMSs (Initial and Extended), analyzed a total of 5,409 publications, from which 65 studies were selected for data extraction. Most publications were categorized as "validation research" and originated from the fields of Computer Science (53.8%) and Engineering (33.8%). The Extended SMS revealed a broader disciplinary diversity, with studies also emerging from areas such as Design and Medical Sciences. Geographically, the majority of the studies came from Europe, North America, and Asia, with the United States, China, and the United Kingdom being the most represented countries. Regarding publication venues, most works appeared in prominent conferences such as IEEE VR, ISMAR, and ACM CHI.

The most frequent quality criterion found in evaluation technologies was usability, although its exclusive predominance dropped significantly from the Initial to the Extended SMS (from 80.2% to 56.4%). Conversely, ETs focused on UX saw a significant rise (from 18.9% to 41.5%), indicating an increasing interest in hedonic and subjective aspects of interaction with THS. However, only 1.5% of ETs addressed both usability and UX together, highlighting an ongoing challenge in developing comprehensive tools that encompass both pragmatic and hedonic dimensions.

Most ETs employed inquiry-based methods, such as interviews and questionnaires (61.7%), followed by user testing (37.6%). While these methods are effective for capturing user perceptions and behaviors, the range of aspects evaluated remains limited. In terms of usability, the most frequently assessed aspects were efficiency (particularly time), effectiveness, and satisfaction. In UX, dominant aspects included "generic UX," "Pleasure/Fun," and "Trustworthiness," while other important dimensions such as Presence and Immersion were still underrepresented. The frequent use of the UEQ questionnaire contributed to broader assessments, though many technologies still evaluated only a single aspect.

Finally, 60% of the ETs were ad hoc, developed specifically for individual studies, reflecting a lack of standardization in evaluation practices. While this approach allows for tailored assessments, it also undermines comparability across studies. Only 36% of ETs employed well-established evaluation technologies such as SUS, NASA-TLX [Hart e Staveland 1988], and UEQ. Moreover, just one ET was proposed and empirically validated, revealing a critical gap in the reliability of tools used to assess THSs. These findings underscore the urgent need to develop robust, empirically validated, and comprehensive evaluation technologies that support reliable assessments of holographic solutions across diverse contexts.

All publications analyzed, as well as the criteria applied, the information extracted and the classifications obtained by the sub-questions can be consulted in technical reports available online [3] [4].

6.2. From Exploratory Search

The exploratory search yielded a comprehensive classification rooted in international standards and widely cited literature. For usability, the study consolidated 17 components such as effectiveness, efficiency, learnability, memorability, error prevention and recovery, controllability, and satisfaction. This last one being further subdivided into usefulness, comfort, trust, and pleasure. These aspects align closely with ISO/IEC 9241-11 [ISO 2018] and ISO/IEC 25010 [ISO 2011], as well as Nielsen's model [Nielsen 2012], offering a structured and multidimensional view of usability. A general aspect, overall usability, was also included to capture the user's global perception.

In parallel, the UX aspects were drawn from key models like Hassenzahl's pragmatic and hedonic attributes [Hassenzahl et al. 2000], combined with elements found in UX frameworks such as UX-TIPS [Marques et al. 2019], Morville's honeycomb [Morville 2004], and Zarour's classification [Zarour e Alharbi 2017]. This effort resulted in a set of 12 UX aspects: usability, usefulness, trustworthiness, creativity and innovation, stimulation, value, beauty and aesthetics, desirability, generic UX, satisfaction, pleasure/fun, and emotional. Notably, immersion and presence were introduced as separate, complementary aspects, reflecting objective system fidelity and the user's subjective sense of integration with the holographic environment, respectively. All aspects identified in the exploratory search and groupings carried out can be viewed in a high-resolution image available online [5].

6.3. From Expert Validation (Study 1)

Study 1 involved 13 experts with diverse backgrounds in terms of education, age, gender, and professional experience. Most participants held a doctoral degree (8), followed by four with master's degrees and one with a bachelor's degree. Their academic backgrounds included Computer Science, Engineering, Design, and Sciences. They reported experience in usability and UX evaluations in both academic and industrial settings. Nine participants declared expertise in usability, 11 in UX, and eight in virtual reality. Additionally, nine had previous experience using touchable holographic, augmented, or mixed reality systems.

Quantitative results revealed strong acceptance of UUXE-ToH v1 in terms of structure and content. Most participants agreed that the questionnaire was appropriate for evaluating usability and UX in THS (84.6%) and deemed its structure, evaluation aspects, and response options to be suitable. The 7-point Likert scale was considered appropriate and easy to understand by 91.7% of respondents. Overall, 82.9% of responses indicated that the items contributed to the evaluation of the intended constructs. The internal consistency measures were also high (Cronbach's alpha = 0.96; McDonald's omega = 0.97), reinforcing the reliability of the instrument evaluation.

[3] Initial SMS Technical Report: https://doi.org/10.6084/m9.figshare.22114355.v1
[4] Extended SMS Technical Report: https://doi.org/10.6084/m9.figshare.26261951.v2
[5] Grouping Aspects: https://doi.org/10.6084/m9.figshare.27806355

Qualitative analysis supported these findings, revealing favorable perceptions of the questionnaire's usefulness, applicability, and completeness. However, several experts noted the questionnaire's length as a potential issue, indicating it could become tiring to complete. Suggestions for improvement included revising technical terms, rewriting or removing specific items, thematic grouping of questions, and standardizing terminology. Some experts recommended a modular structure to allow adaptation of the questionnaire to different evaluation contexts. Overall, the feedback highlighted UUXE-ToH v1 as a relevant and promising tool, while also indicating important directions for refinement in its next version.

The published thesis presents all the instruments used in the study, in full. A high-resolution image available online presents the axial coding of the qualitative analysis [6], and a spreadsheet with the processed feedback codes from Content and Face Validation that served as a basis for refining UUXE-ToH v1 into UUXE-ToH v2 is also available [7].

6.4. From End-User Validation (Study 2)

Study 2 involved 260 participants recruited from five Brazilian universities, with diverse age groups, gender identities, and levels of familiarity with technologies such as AR, MR, and holography. Most participants used the Meta Quest 2 headset and interacted with the Cubism game for the first time during the study. The average completion time for the UUXE-ToH v2 questionnaire was approximately 13 minutes, which was considered satisfactory given the instrument's length and complexity. Preliminary analysis revealed non-normal distributions and partial lack of response category representation in some variables, justifying the decision not to impute missing data in subsequent analyses.

Semantic validity was supported by positive participant evaluations regarding clarity, coverage, and ease of use. Quantitative analysis showed high internal consistency (Cronbach's alpha and McDonald's omega above 0.75), while qualitative feedback highlighted some redundancy, suggestions for streamlining, and wording improvements. Internal consistency was acceptable or good for most constructs, notably Immersion, Comfort, Stimulation, and Emotions. Constructs such as Presence showed borderline reliability, and Learnability had low reliability, indicating the need to revise or remove specific items. EFAs revealed coherent factors for aspects such as Comfort, Emotions, and Controllability, while other factors exhibited mixed item groupings or limited robustness, suggesting the need for theoretical and structural refinements. Discriminant validity was confirmed by mostly low to moderate correlations between constructs, supporting their distinction.

Finally, convergent validity was demonstrated through positive and statistically significant correlations between UUXE-ToH usability constructs and SUS scores, particularly for Effectiveness, Usefulness, and Satisfaction. Comparisons with the UEQ also revealed moderate correlations between corresponding aspects, reinforcing UUXE-ToH's alignment with established UX measures.

The published thesis presents all the instruments used in the study, in full. A high-resolution image available online presents the axial coding of the qualitative analysis of

[6] Axial Coding for Content and Face Validation: https://doi.org/10.6084/m9.figshare.27665688
[7] Spreadsheet of Processed Feedback on UUXE-ToH v1: https://doi.org/10.6084/m9.figshare.27822558

semantic validity [8], and a spreadsheet with the processed feedback codes from Semantic Validation that served as a basis for refining UUXE-ToH v2 into UUXE-ToH v3 is also available [9]. The collected data [10] and R script source codes [11] used in the analyses of this study are also available, as well as the reports generated from the ACIs and EFAs in the JASP software [12].

6.5. From Evaluators Validation (Study 3)

Study 3 involved 14 participants, divided into two groups: Group A, which used the UUXE-ToH v4 questionnaire, and Group B, which used the combination of USE+SUS+UEQ. Participants evaluated a THS and reported usability and UX issues they identified during the experience. Group A identified 31 issues (26 unique), while Group B reported 15 (14 unique), with statistically significant differences between the groups in both the total number of problems and the coverage rate. Group A was more effective in detecting issues related to aspects such as Effectiveness, Learnability, Controllability, Error Prevention, Trustworthiness, Aesthetics, and Presence. Both groups found an equal number of issues related to Immersion, while Group B stood out only in identifying a Comfort-related issue.

In terms of efficiency, the average inspection time was higher in Group A (11 minutes) compared to Group B (6 minutes), but the rate of problems identified per minute (VPT) was slightly higher for Group A (2.82 vs. 2.50). Statistical tests did not show significant differences in these efficiency indicators, suggesting that the more detailed performance observed in Group A did not compromise participant efficiency. Regarding the acceptability of the evaluation technologies, TAM data revealed a slight advantage for UUXE-ToH v4 in the constructs of Perceived Ease of Use and Behavioral Intention, with the latter showing statistically significant differences. Qualitative feedback reinforced positive perceptions of the UUXE-ToH v4 as a practical and useful tool to guide evaluation processes, while also pointing out challenges such as the difficulty of recalling past interactions to report issues effectively.

The published thesis presents all the instruments used in this study, in full. The data collected in the TAM forms, as well as the information extracted from the problem identification form, were gathered with a spreadsheet and analysis and report files from the JASP software, and are available for consultation [13].

These findings highlight the robustness of the UUXE-ToH as an evaluation technology tailored to the complexities of interactions with holograms. The integration of usability and UX dimensions into a single tool enhances efficiency, reduces participant fatigue, and enables richer, more holistic assessments. Furthermore, the methodological rigor of the questionnaire, including expert input, user-centered validation, and psychometric testing, strengthens its contribution to the field of HCI and supports its applicability in education, health, and entertainment contexts involving AR/MR systems.

[8] Axial Coding for Semantic Validation https://doi.org/10.6084/m9.figshare.27822543
[9] Spreadsheet of Processed Feedback on UUXE-ToH v3: https://doi.org/10.6084/m9.figshare.27822549
[10] Collected data from Study 2: https://doi.org/10.6084/m9.figshare.26970676
[11] R Scripts Used in Study 2: https://doi.org/10.6084/m9.figshare.27000478
[12] JASP Reports for ACIs and EFAs: https://doi.org/10.6084/m9.figshare.26972458
[13] Data, Scripts and Reports of Study 3: https://doi.org/10.6084/m9.figshare.27822213

The results also reinforce the importance of developing domain-specific evaluation tools that reflect the nuances of emerging technologies. The UUXE-ToH not only addresses a documented gap in the literature but also sets a precedent for future instruments seeking to balance rigor with practical usability in immersive environments.

7. Limitations

This research faced methodological, contextual, and operational limitations that affect the generalizability and scope of its findings, particularly within the emerging domain of THS. In the mapping studies, the absence of a unified definition of "holography" and the evolving nature of the field may have limited the coverage of relevant literature. Despite broad search strategies and expert cross-review, findings were constrained to studies available up to April 2023.

The content and face validation of UUXE-ToH v1 involved a small group of Brazilian experts, with varied experience and limited exposure to THS. This affected the generality and neutrality of feedback. Likewise, the user validation was context-bound, focusing on a single game (Cubism) using Meta Quest devices, which limits applicability to other scenarios and technologies.

Access to THS-ready equipment was also a significant constraint, due to high costs and limited availability in academic settings. This hindered large-scale testing and restricted the types of applications that could be evaluated. The questionnaire's length, and the use of other questionnaires to assess the solution, posed challenges in terms of participant fatigue and recruitment logistics. The need for in-person sessions using immersive devices, combined with time-consuming ethics approval processes, added complexity to the study design.

Lastly, the acceptance study was affected by limited interaction time, a small and uneven sample, and constraints of the evaluation environment, reducing the depth and generalizability of the findings. Future work should expand to more diverse samples and evaluation contexts, pursue cross-cultural validation, and leverage interinstitutional collaboration to overcome equipment and recruitment barriers.

8. Ethical Considerations

This research followed strict ethical principles across all stages, from study design to data collection and dissemination. All empirical investigations involving human participants were reviewed and approved by relevant Research Ethics Committees (RECs), in compliance with Brazilian national regulations (Resolution No. 466/12 of the National Health Council) and institutional standards for research involving human beings.

- **Study 1:** Approved by the REC of the Federal University of Paraná (UFPR), Certificate of Presentation for Ethical Consideration (CAAE) 68509423.0.0000.0102, under opinion no. 6,103,079 (June 6, 2023), with final report approved under opinion no. 6,642,477 (February 8, 2024).
- **Study 2:** Approved by the REC of UFPR (CAAE 77369524.6.0000.0102, opinion no. 6,704,224) and co-participating institutions:
  - Universidade Tecnológica Federal do Paraná (UTFPR), CAAEs 77369524.6.3003.5547 e 77369524.6.3004.5547, opinions no. 6,817,175 and 6,813,655;

  - Santa Catarina State University (UDESC), CAAE 77369524.6.3001.0118, opinion no. 6,801,870;
  - Federal University of Ouro Preto (UFOP), CAAE 77369524.6.3002.5150, opinion no. 6,946,494.

  Final reports were submitted on January 21, 2025, and have been approved by UFPR, UTFPR, and UDESC; UFOP's review is pending.
- **Study 3:** Approved as an amendment to project 77369524.6.0000.0102 by UFPR under opinion no. 7,111,664 (September 30, 2024).

All participants were informed about the study objectives, procedures, potential risks (such as cybersickness or fatigue), voluntary nature of participation, and their right to withdraw at any time without consequences. Informed consent was obtained either electronically or in writing, as specified in each study protocol. Data were anonymized and stored securely, with no personally identifiable information being collected.

To ensure physical safety, experimental environments were prepared to be clean, well-lit, and obstacle-free, with participants seated throughout the study. Equipment was sanitized before and after each use. Researchers closely monitored for signs of fatigue or discomfort, offering rest periods when needed and pausing the study if necessary. Participants who experienced cybersickness or similar symptoms were encouraged to stop, rest, or withdraw at any point.

Although psychological support was made available at no cost (provided remotely by a licensed psychologist) no participant requested this service during or after participation. Likewise, there were no instances requiring medical or nursing intervention. All participants completed the study procedures as planned. The preventive measures adopted, including detailed explanations, controlled environments, and optional breaks, were effective in minimizing risks and promoting participant well-being. No adverse events or post-study concerns had been reported.

Exclusion criteria were clearly defined to avoid recruiting individuals more susceptible to risks from immersive environments, such as those with a history of seizures, migraines, or motion sickness. Pregnant individuals and those with contagious illnesses were also excluded to safeguard the health of all participants.

Beyond formal compliance, the research demonstrated a broader ethical commitment by ensuring the accessibility and neutrality of questionnaire items, supporting inclusive participation, and guaranteeing freedom of choice during all procedures. Participants were never pressured or rushed and were free to take breaks, eat, drink, or leave at any time. By maintaining transparency, respect, comfort, and safety, this study exemplified ethically responsible research practices in HCI.

9. Publications, and Products from Research

The main publications resulting from this research were:

1. Chapter **Avaliação da Usabilidade e da Experiência do Usuário em Realidade Virtual e Aumentada**, published in the book *Minicursos IHC 2024 — Fundamentos e Práticas para Experiências Digitais Acessíveis, Inclusivas e Eticamente Responsáveis*. DOI: 10.5753/sbc.16123.0.3.

2. Chapter ***Evolution of a Usability and UX Questionnaire for Touchable Holography After End-Users Feedback***, accepted for publication in Lecture Notes in Business Information Processing.
3. Article **Evaluating Usability and UX in Touchable Holographic Solutions: A Validation Study of the UUXE-ToH Questionnaire**, published in the *International Journal of Human-Computer Interaction (IJHCI)*, Taylor & Francis, 2024. DOI: 10.1080/10447318.2024.2400755.
4. Paper ***Usability and User Experience Evaluation of Touchable Holographic Solutions: A Systematic Mapping Study***, presented at the *Brazilian Symposium on Human Factors in Computing Systems (IHC 2023)*, in Maceió, Brazil. DOI: 10.1145/3638067.3638071.
5. Article **Usability and UX Evaluation in a Mixed Reality Puzzle Game Using Questionnaires**, published in the *Journal on Interactive Systems (JIS)*, August 2025. DOI: 10.5753/jis.2025.6089.
6. Article ***An Updated Systematic Mapping Study on Usability and User Experience Evaluation of Touchable Holographic Solutions***, published in the *Journal on Interactive Systems (JIS)*, January 2025. DOI: 10.5753/jis.2025.4694.
7. Paper ***Evaluating Usability, User Experience, and Playability of a Puzzle Game in Mixed Reality***, presented at the *26th Symposium on Virtual and Augmented Reality (SVR 2024)*, in Manaus, Brazil. DOI: 10.1145/3691573.3691584.
8. Paper **Evaluating Performance and Acceptance of the UUXE-ToH Questionnaire for Touchable Holographic Solutions**, presented at the *27th International Conference on Enterprise Information Systems (ICEIS 2025)*, in Porto, Portugal, April 2025. DOI: 10.5220/0013447100003929.
9. Paper ***Usability and User Experience Questionnaire Evaluation and Evolution for Touchable Holography***, presented remotely at the *26th International Conference on Enterprise Information Systems (ICEIS 2024)*. DOI: 10.5220/0012564100003690.

This doctoral research also resulted in the design and development of a tool to support collaborative literature reviews. This is Porifera [14] [Campos et al. 2022a, Campos et al. 2022b, Prado De Campos et al. 2023], a web application that obtained software registration with the National Institute of Intellectual Property (INPI), number BR512021002069-3 on August 25, 2021. Porifera has already been used by several other researchers free of charge (e.g. [Izo et al. 2023, Filho et al. 2023, De Souza et al. 2023, Silva et al. 2024, Mariano et al. 2024, Haddad et al. 2024]). The tool also underwent user evaluations and was publicized through three publications, shown below.

1. Article ***Evaluating a Collaborative IS to Support Systematic Literature Reviews and Systematic Mapping Studies***, published in the journal *iSys: Brazilian Journal of Information Systems*, 2023. DOI: 10.5753/isys.2023.2919.
2. Paper ***Porifera: A Collaborative Tool to Support Systematic Literature Review and Systematic Mapping Study***, presented remotely at the *26th Brazilian Symposium on Software Engineering (SBES 2022)*. DOI: 10.1145/3555228.3555273.
3. Paper ***Proposal and Evaluation of a Collaborative IS to Support Systematic Reviews and Mapping Studies***, presented at the 18h *Brazilian*

[14] https://porifera.app.br

Symposium on Information Systems (SBSI 2022), in Curitiba, Brazil. DOI: 10.1145/3535511.3535531. **This work received an honorable mention for the quality of the research.**

10. Contributions to the HCI Field

This research offers significant contributions to the HCI field by advancing the evaluation of emerging interaction paradigms, particularly in immersive contexts such as AR and MR. The development of the UUXE-ToH questionnaire addresses a critical gap identified in the literature: the lack of a unified, domain-specific instrument capable of evaluating both usability and UX in THS.

One of the main scientific contributions is the creation of a theoretically grounded and empirically validated evaluation tool that incorporates both pragmatic (e.g., effectiveness, efficiency, controllability) and hedonic (e.g., pleasure, emotions, presence) aspects. Unlike existing instruments, which were developed for general systems and often require combination to cover multiple dimensions, UUXE-ToH integrates them into a single coherent framework, avoiding redundancy and increasing evaluation efficiency.

Methodologically, this work contributes a multi-phase validation strategy that combines expert evaluations, end-user feedback, statistical validation (exploratory factor analysis), and comparative performance assessments. This rigorous approach ensures both scientific robustness and practical applicability. It also offers a replicable model for the development of evaluation instruments in other emerging domains of HCI.

From a technical standpoint, the UUXE-ToH enables more precise and meaningful evaluations of THS interfaces, promoting better-informed design decisions. By capturing user perceptions in immersive, mid-air gesture interaction contexts, the instrument supports the early detection of design flaws and usability bottlenecks that may not be captured by generic tools.

Socially and educationally, the questionnaire contributes to broader access and understanding of evaluation practices in immersive systems. Its accessibility to evaluators with varying levels of experience in UX promotes its use in diverse application areas, including education, healthcare, training, and entertainment. The open availability of the instrument and its documentation facilitates adoption and adaptation by researchers and professionals in different regions and institutions.

In summary, this work enriches the HCI landscape by delivering a validated, context-aware tool that not only fills a theoretical and practical gap in THS evaluation but also exemplifies best practices in the development of instruments for next-generation interactive technologies.

11. Conclusion and Future Works

This research addressed a critical gap in the evaluation of interactive systems by proposing and validating UUXE-ToH, a comprehensive questionnaire designed to assess both usability and UX in THS. Developed through a rigorous and iterative process, that included literature mapping, expert evaluation, semantic validation, and empirical testing, UUXE-ToH emerged as a robust and domain-specific instrument capable of capturing pragmatic and hedonic aspects of user interaction in immersive AR/MR environments.

The final version, UUXE-ToH v4, incorporates 56 items across 19 carefully defined aspects, reflecting structural refinements and empirical insights. Studies demonstrated the questionnaire's ability to detect more usability and UX issues than traditional instruments, while maintaining clarity, consistency, and strong acceptance among evaluators.

Despite its strengths, the research has limitations. The validation studies were conducted in specific contexts (e.g., a puzzle game in MR using Meta Quest devices), with limited demographic diversity and constrained access to THS-compatible technologies. The length of the questionnaire, logistical demands of in-person testing, and reliance on a narrow set of applications also present challenges for generalization and scalability.

Looking ahead, several directions for future work have been identified. These include broadening the scope of UUXE-ToH through application in diverse scenarios, platforms, and user groups, and establishing partnerships with academic and industry stakeholders to encourage adoption in real-world evaluation pipelines. Continued enhancement of the digital platform is planned to further support its practical use.

Additional research may explore the use of shortened or modular versions of the questionnaire for rapid assessments, as well as integration with complementary methods such as heuristic evaluation by inspection. Cross-cultural validation and translation into other languages will be important steps toward expanding the global applicability of the tool. Moreover, future studies could leverage advanced statistical techniques, such as Structural Equation Modeling (SEM), to further investigate the relationships between constructs and enhance structural validation.

Ultimately, this work delivers more than a measurement instrument: it introduces a comprehensive, validated solution for evaluating emerging interactive technologies. By combining methodological rigor, user-centered design, and practical accessibility, UUXE-ToH contributes to improving the design, assessment, and adoption of next-generation immersive experiences. Future developments aim to consolidate it as a reference tool in both research and industry contexts.

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