The EXtended Reality Quality Riddle: a Technological and Sociological Survey

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***Abstract*—This position paper surveys recent research on the latest findings regarding the Quality of Experience in XR from two distinct angles. Firstly, we present recent technical outcomes concerning media quality. Secondly, we extend our investigation to user experiences from a sociological perspective. This innovative multidisciplinary approach establishes a connection between various methodologies, enabling a more comprehensive understanding of XR quality and it opens up new possibilities for XR services design and performance measurements.**

***Keywords*—(Extended reality, Quality of Experience, Affordance)**

1. Introduction

The problem of eXtended Reality (XR) Quality of Experience evaluation is extremely challenging. The XR services encompass a wide range of multimedia services that involve synthetic objects (Virtual Reality,VR), enhanced natural objects (Augmented Reality, AR), and combinations of natural and synthetic multimedia objects. The enriched multimedia content conveyed by XR data enables numerous applications, such as training [1,2], creative production [3], and maintenance or security [4]. In such a lively framework, it is relevant to identify key quality attributes of the XR services.

Quality evaluation for XR services is still an open problem. From a technical point of view, each kind of media data (natural, synthetic, textual objects). is characterized by specific perceptual quality metrics. Furthermore, each application comes with different requirements and users' expectations. For a given XR service and kind of data the perceived quality is related to media features such as spatial or temporal resolution, color naturalness and pleasingness. Besides, it is related to time related features, such as fast rendering or display rate. Furthermore, XR services typically require novel interfaces, whose design, for instance in terms of shape, weight, ease of use, definitely determines the user experience. Finally, XR services often aim at inducing experience such as involvement, sense of presence, natural interaction with mixed reality objects, as well as engagement feeling. Therefore, a discussion on XR quality necessarily involves different methodological and scientific tools.

Herein, we tackle the problem from an interdisciplinary point of view. Specifically, after reviewing some open XR research challenges, we survey recent results on XR Quality of Experience from a twofold point of view. On one hand, recent technical results on media quality are reported; on the other hand, the study is extended to account for sociological results about the user experience (UX). This multidisciplinary approach is novel and lays a bridge between different methodologies, paving the way for a more comprehensive understanding of XR quality.

2. XR Services: Open Research Challenges

XR services involve a wide range of data kinds, pose a challenge to communication infrastructures, and are used within a variety of services. For the sake of concreteness, we shortly summarize here a few research challenges appearing in the recent technical literature. We restrict ourselves to XR teaching/learning/training applications, and to 5G/6G communication infrastructures, leaving an extensive analysis of XR for data visualization applications for further study.

Recent literature on XR teaching/learning/training applications addresses a relevant set of topics, as reported in Fig.1 and visually summarized in Fig. 2. The study in [35] focuses on the application of XR for autistic individuals, examining their autonomy, human-computer interaction, and the sense of presence. In [36], the authors study interactive information visualization in immersive environments, encompassing aspects like immersive analytics and infographics. The study in [37] demonstrates how immersive virtual field trips grant students access and interaction to field activities not feasible in real-world settings. In [38], it is highlighted that fully immersive VR is well-suited for procedure training, but MR boosts procedural cognition skills. The work in [39] addresses a gap in practical XR solutions for teachers and instructors. In [40], a theoretical framework is presented, comprising instructional design, knowledge, research and technology, and talent and training hubs for XR in education. Furthermore, XR's positive impact in terms of engagement and safety is discussed in [41] on demonstration-based training. Additionally, [42] explores XR potential features for language education, covering aspects like design, pedagogy, technology, actors, and learning dimensions.

For such services, the availability of high throughput, low latency communication channels is a key enabling factor: when there is not a perfect synchrony between actions performed and what happens in the XR environment, the immersion is less and therefore the user experience becomes less satisfying. Several XR communication solutions are currently under investigation: the main trends -plotted in Fig.3 and summarized in Fig. 4- include the development of low-latency XR services exploiting edge network resources, with different optimization objectives ranging from efficient bandwidth employment to reduced energy consumption. The authors in [43] introduce a Deep Reinforcement Learning-based offloading scheme for XR devices at the network edges such as base stations or WiFi access points. The work in [44] studies the challenge of real-time free-viewpoint video services using 5G key technological enablers: mmWave radio access network, multi-access edge computing, and end-to-end slicing, also identifying areas of improvement for higher quality of experience in next generation networks. In [45] VR visors traffic profiling during multi-party interactions is addressed. The paper collects real trace data to analyze temporal correlation, and to derive prediction models for future frame sizes. The paper [46] focuses on designing control policies for the joint orchestration of compute, caching, and communication resources in next-generation networks for data-intensive AR services, optimizing decisions on routing and distribution, as well as processing and caching associated with data objects. In [47], a Long Short-Term Memory (LSTM) network is employed to forecast immersive video content requests and prefetch content to caches. In [48], Colocation Edge Computing (ColoMEC) is proposed, wherein multiple operators share the same BS tower and radio and computation resources. Optimal joint bandwidth allocation and micro-datacenter sharing is pursued. The authors in [49] propose a novel framework called MetaSlicing, offering an effective solution to manage and allocate different types of resources for Metaverse applications: applications clusters sharing common functions are addressed using an intelligent admission control algorithm based on semi-Markov decision process, optimizing resource utilization and enhancing quality of service for end-users.

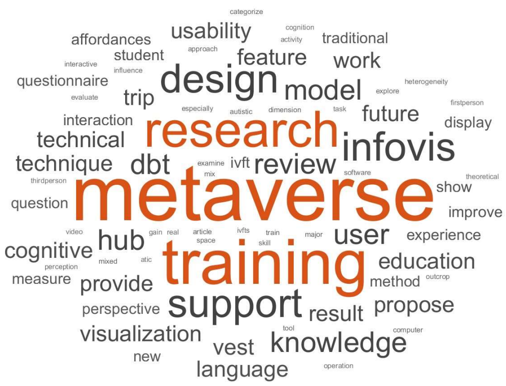

Figure 2: Word bubble from the XR for learning literature (source data: IEEE Xplore Transactions, 2018-2023)

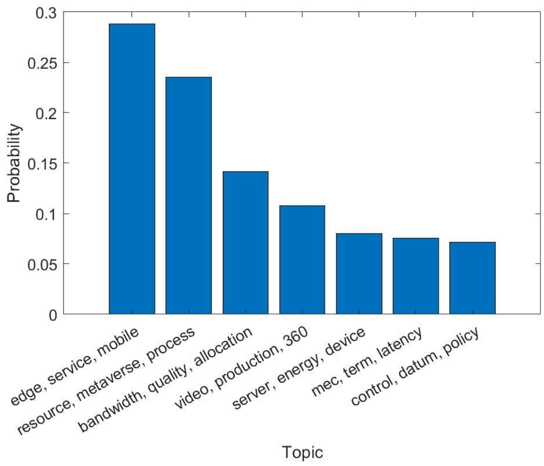

Figure 3: Key topics emerging from the XR communication literature, and related frequency of occurrence (source data: IEEE Xplore Transactions, 2018-2023).

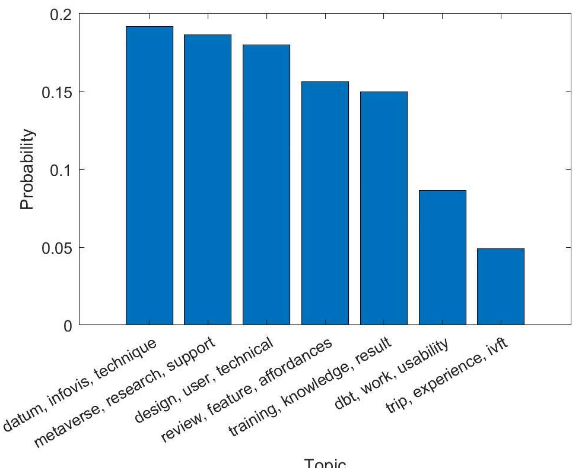

Figure 1: Key topics emerging from the XR for learning literature, and related frequency of occurrence (source data: IEEE Xplore Transactions, 2018-2023).

Figure 4: Word bubble from the XR communication literature (source data: IEEE Xplore Transactions, 2018-2023)

To sum up, XR services on one hand pose technical challenges, and their performances can be assessed in terms of technically related metrics (throughput, latency, rendering fidelity); on the other hand, the impact of the final user experience depend on a wider range of features, related to psychological and sociological levels. With this in mind, in the following we analyze the key factors affecting the XR quality under this twofold point of view.

3. XR SERVICES: A GLIMPSE ON QUALITY OF EXPERIENCE

XR media acquisition is achieved using readily available devices like Red Green Blue plus Depth (RGB-D) or Time of Flight (TOF) cameras, as well as LIDAR [5]. Additionally, XR data can be extracted from conventional video sequences [6]. Typically, XR data is represented as point clouds, which are sets of points in 3D space. Each point may possess attributes like luminance and chrominance. While there have been efforts to standardize XR compression techniques [7], efficient point cloud compression remains an active area of research [8].

Ongoing standardization [9] encompasses various XR communication services, including gaming, and primarily focuses on two service architectures: streaming services and conversational services. These architectures have distinct requirements, with streaming services focused on low-jitter and conversational services focused on low-delay. XR streaming is particularly relevant due to the exponential growth of mobile streaming traffic requests [10].

The performances of XR services can be measured in terms of the user Quality of Experience (QoE). QoE is related to key quality indicators of the transport network, showing that 5G can effectively support such services [20]. In [23], ITU-T addressed a QoE prediction model for gaming services. A QoE model for mobile gaming in presence of communication channel errors and delays appears in [24], whereas network latency is addressed in [25]. XR service QoE evaluation is also challenging since the perceived quality depends on the content, the user gender, the daily exposure time, at least at medium to high delivery quality (low delay)[19]. The subjective video quality affects QoE relevant factors as sensory immersion and simulator sickness scores, measured by EEG user activity [18], whereas the augmented reality quality accounts for text features (e.g. readability) [21]. Even the level of users' familiarity with the service affects the perceived QoE, e.g. gamers exhibit a high level of sensitivity or criticality towards increased levels of delay, especially if they are experienced gamers [17].
Furthermore, the kind of XR services may result in significant interaction with the users. As a matter of example, in cultural heritage applications [26] the users may engage the XR data with specific behavior. This reaction can be analyzed and predicted to provide better support to the service. On the other hand, XR services may affect the user personal space boundaries [16], so that female AR characters, likely perceived as more friendly or less threatening due to gender-stereotypes, are allowed a closer interaction. Besides being characterized in terms of Quality of Experience, XR services may be characterized by their detrimental effects, ranging from cybersickness even to muscle pain, fatigue, discomfort due to headset weight or fit [22].
Assessing QoE is a global and significant way for XR based applications is evidently a complex task. It is rooted in engineering metric that measure data integrity, transfer delay and delay variation, throughput of data delivery. It also covers Human-Machine Interface aspects, usability of the application, accessibility on different devices. Given the specific nature of XR application, QoE encompasses also psychological and sociological issues, e.g., perception, emotional engagement, enrichment of the interaction experience. These last aspects are especially a major challenge in capturing QoE of XR applications in a limited range of quantitative measures.
In a nutshell, XR QoE measurement is still an open problem, and any objective metric used to measure XR QoE should meet four specific criteria [27]:

1. The metric should assess social and spatial presence, as well as their sub-components (co-presence + social interaction and telepresence + agency).
2. The metric should take into account both internal (individual) and external (observed by others) evaluation perspectives.
3. Metrics should cover all relevant processing levels, including sensory, emotional, cognitive, reasoning, and behavioral aspects.
4. The metric should evaluate the experiential fidelity of the communication system, that is, its inherent ability to provide a realistic and natural communication experience.

4. XR AFFORDANCE

Limited usability and ineffective user interfaces can undermine user acceptance of XR technologies, leading to the question of "What affords and what constrains the XR experience?" This question relates to the concept of affordance [11], which refers to the "multifaceted relational structure" between an object/technology and the user, determining potential behavioral outcomes in a given context [12].

This relational perspective helps explain why there is no single theory of affordances, as they emerge from the interaction between users, the material characteristics of technologies, and the contextual nature of use.

The concept of affordance is commonly discussed in studies on technology and interaction. Shin [13] introduced the concept of technological affordance and affective affordance in virtual reality, specifically in the context of interface design. The technological affordance of immersion and presence empowers users to shape the physicality of the extended reality experience, while the affective affordance of empathy and embodiment allows users to influence the design of extended reality by empathizing with and embodying the experience. Furthermore, affordances in XR result from user interactions with technological artifacts. For example, immersion is not pre-made, but built through player input, which is in turn driven by the perceived 'materiality' of the system. It follows that extended reality is not entirely enabled by technology, but by the offers that users perceive. With this in mind, to improve the performance of the XR, priority should be given to user accessibility together with technological qualities.

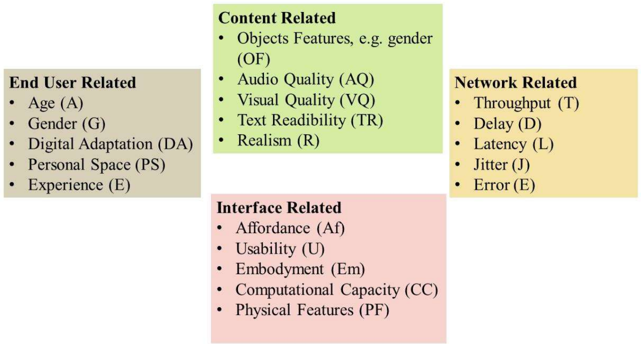

Figure 5: Key factors affecting the quality perceived by the user.

In the realm of XR, the relationship between individuals' capabilities and the properties of XR objects takes on great significance when designing XR as a user-centered artifact. XR offers similar affordances as previous realities but at a heightened level of realism and immersion, as it extends beyond conventional realities [14].

Given the extensive range of behavioral options available to users in an XR environment, understanding how the choice of actions for a particular affordance influences its actual utilization becomes crucial. Discovering affordances is paramount for usability, particularly in XR scenarios where users can align potential uses of XR with their cognitive models. To create a system that caters to people's needs, comprehending its affordances and integrating them into the design process is of utmost importance [15].

5. XR OUTREACH

Age and gender are commonly studied variables in XR adoption and the perception of quality. Regarding age, studies suggest that Generation Z individuals prefer new technologies, particularly XR, due to the opportunities for simulation and experimentation that this modern technology provides [28].
When it comes to gender, however, men tend to report a stronger sense of spatial presence, a higher perception of realism, and a greater feeling of being immersed in the XR environment compared to women [29]. Additionally, women are more than twice as likely as men to experience discomfort or feelings of illness when using VR/XR technologies [30]. As a result, the quality of the XR experience may be perceived differently by men and women, as well as by individuals from different generations. Therefore, it is important to develop gender- and age-sensitive metrics for XR QoE, conducting analyses that include both men and women of different ages during development and testing.

Furthermore, regarding the digital divide, specific studies on the impact of the digital divide on the perceived quality of XR technologies are lacking. However, it can be assumed that the findings from various researches on other topics are also applicable to XR. Individuals who are more digitally adept consider technology to be a useful tool in their daily lives and exhibit a higher level of satisfaction when using different devices [31]. Future work is needed to address the role of XR in creative reasoning [34]. Finally, technological opportunities for inclusion and diversity shall be explicitly pursued at a technological, social and political level [33].
XR could also play a major role in enhancing quality and effectiveness of people meeting and working together. As a matter of example, the recent COVID-19 pandemic forced many scientific events and conferences to be held in a virtual remote mode. Networking and exchange of ideas was quite hurt and tools to address this use were provided, e.g., Gather Town (https://www.gather.town/).
It is apparent how XR could greatly improve such applications, as well as work from home, remote teaching, technical meetings. Without aiming to replace in presence contacts, which are anyway fundamental, still XR based applications could help reduce significantly wastes of time and pollution due to many people moving even over great distance to meet up and have an effective cooperative work and interaction experience.

To sum up, the evaluation of the quality perceived by the user, requires a multidisciplinary approach, encompassing several factors, listed in Fig.1. As a possible tool for concurrent evaluation of all the factors, we propose the Quality Experience Wheel represented in Fig. 2. The Quality Experience Wheel is a polar plot, where different aspects, pertaining to Content (green), Interface (pink), User (brown), and Network (yellow), are grouped in different sections of the wheel. For each group, a set of factors is identified as follows. For the group of *Content* related features, we have identified Audio Quality (AQ), Visual Quality (VQ), Text Readibility (TR), Objects Features, e.g., gender of the AR character (OF), Realism (R). For the group of *Interface* related features, we included Affordance (Af), Usability (U), Embodyment (Em), Computational Capacity (CC), Physical Features (PF). As for the *Network* related features, we considered Throughput (T), Delay (D), Latency (L), Jitter (J), Error (E). As for the User related features, we finally considered Age (A), Gender (G), Digital Adaptation (DA), Personal Space (PS), Experience (E). Each factor is represented by a sector of different radius corresponding to a specific metric. The joint polar representation of the metric corresponding to significant factors can be adopted as a "quality signature" of the XR services and provide a tool for services comparison and experiments' design.

6. CONCLUSION

In this position paper, we tackled the problem of XR quality with a multidisciplinary approach. We focused on examining the Quality of Experience in XR (Extended Reality) from two perspectives. Firstly, we analyzed the recent technical findings regarding media quality. Secondly, we have addressed sociological findings about the user UX. This unique multidisciplinary approach establishes connections between various methodologies, leading to a broader and deeper comprehension of XR quality.

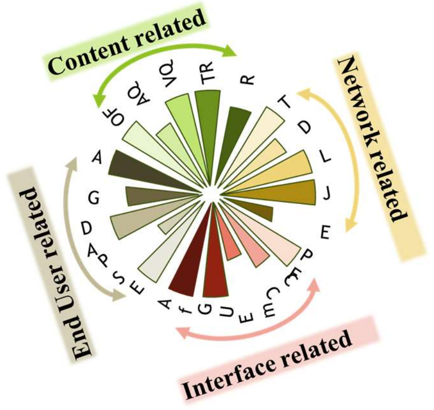

Figure 6: The Quality Experience Wheel as a "quality signature" of the XR services.

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