Stars Without Steps: Bridging Observatory Access Based on Physical Proximity Through Educational XR

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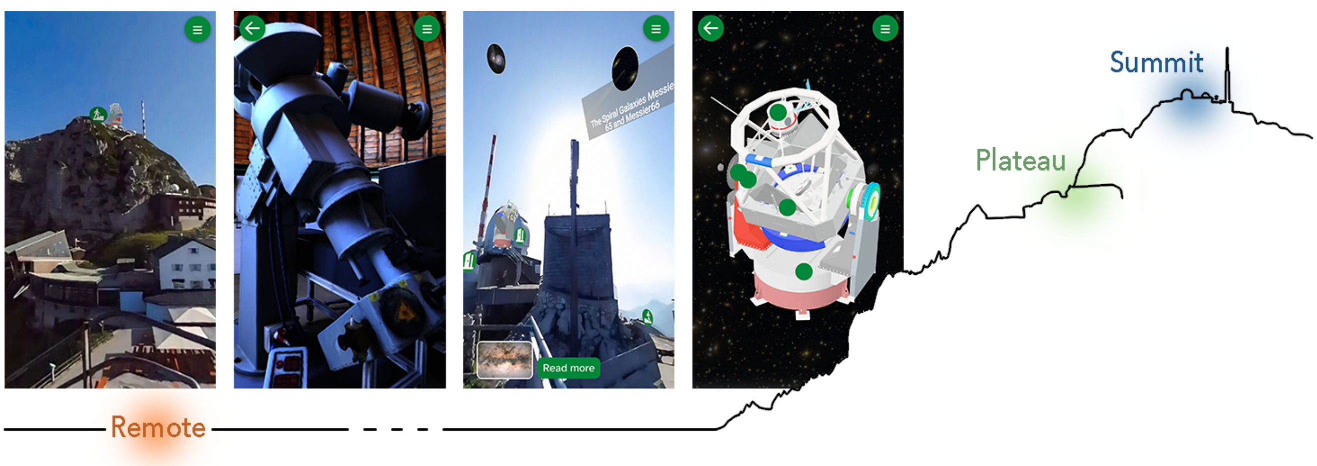

Figure 1: In this paper, we evaluate the influence of physical proximity on mental load, presence, motivation, perceived access, and quiz results with 35 upper grade students using a mobile observatory XR application.

Abstract

Remote research facilities such as mountain observatories offer unique scientific and educational value, yet their physical inaccessibility limits participation for many audiences. This paper presents a location-independent, mobile Extended Reality (XR) application that extends the experiential reach of a mountain-based observatory beyond its geographic constraints. The application allows users to virtually explore a research telescope and interactively learn about the observatory's scientific work, instrumentation, and operational principles. Following interviews with on-site visitors to identify access barriers and learning needs, we developed an XR experience and evaluated it in an in-the-wild study with three school classes (N = 35). We deployed the application across three contexts (remote location, intermediate plateau, mountain summit) and assessed factors such as mental load, presence, motivation, perceived access, and quiz results. Our findings indicate that context-dependent physical proximity influences all factors except the quiz outcome, highlighting the importance of proximity-aware design for future XR systems.

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CCS Concepts

• **Human-centered computing** → **Mixed / augmented reality**; • **Applied computing** → *E-learning*.

Keywords

Extended Reality, Mobile, Education, Proximity, Observatory

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1 Introduction

Many places of scientific, cultural, or educational significance remain inaccessible to large parts of the population. Physical distance, health constraints, safety regulations, and limited institutional access often prevent learners from experiencing such sites firsthand. Astronomical observatories are a prominent example: typically located in remote and elevated regions to ensure optimal observation conditions, they are difficult to reach and rarely offer regular public tours. As a result, educational engagement with these environments is often restricted to abstract descriptions, images, or videos, limiting experiential learning opportunities. Extended Reality (XR) technologies, including Virtual Reality (VR) and Augmented Reality (AR), offer promising solutions to overcome these barriers by enabling remote virtual and on-site augmented exploration of otherwise inaccessible spaces [13]. Prior work in the educational context has investigated how to design XR experiences that enhance learning [2, 22] and create a sense of presence [11]. However, existing work mostly assumes a fixed usage context [8, 32] and overlooks the user's physical proximity to the represented place. In educational settings, learners may interact with XR applications that give information about specific locations at varying distances from the real-world site: from fully remote locations to being physically near or even at the site itself. The context of equipment use [25] and small variations in physical distance [30] can influence user experience and interaction preferences. Still, little is known about the effects of larger differences in proximity on learning experience and perception in mobile XR applications. To address this gap, we investigate how physical proximity to an inaccessible site affects user experience when interacting with a mobile XR application. Building on insights from a qualitative, formative pre-study, we designed an adaptive mobile XR system that dynamically varies the amount of virtual and real content based on the user's physical location. We then conducted an in-the-wild user study with 35 upper secondary school students using a between-subjects design. Participants interacted with the application from one of three locations: a *remote* site, an intermediate mountain *plateau*, or directly at the observatory *summit*. We analyzed the influence of context-dependent physical proximity on mental workload, sense of presence, motivation, perceived access, and knowledge acquisition through a quiz. Our findings contribute empirical evidence on how proximity-aware XR experiences shape educational outcomes and user experience, offering design implications for future XR systems aimed at making inaccessible places meaningfully accessible.

2 Related Work

Prior work highlights the importance of spatial and contextual proximity for learning [1]. The spatial alignment of information with its referent influences comprehension and retention, with closer proximity generally supporting better learning outcomes [17, 20]. Similarly, learning with equipment in authentic contexts increases perceived relevance and engagement compared to abstract settings [25], suggesting that both informational and physical context shape educational experience. Mobile XR has been widely explored as a means to situate learning content in real-world environments. As XR technologies continue to develop, mobile AR in particular has been shown to be accessible and convenient for diverse users [5, 19, 31]. Studies in environmental education further demonstrate the potential of outdoor mobile AR to support engagement, learning, and storytelling [3, 12, 27]. AR in outdoor and public settings is used as educational tool for connecting classrooms with outdoor spaces [2], public AR installations [23], tourist, cultural heritage and sightseeing applications [18, 27, 28]. Related work even indicates that AR can improve learning about tourist sights compared to traditional methods [6]. Research on outdoor AR systems has addressed technical, perceptual, and interaction challenges: navigation and geographic information visualization [9, 15], development [14], depth perception differences between indoor and outdoor AR [16], interaction across varying physical small distances [30], and multisensory or accessibility-focused approaches [4, 18]. In parallel, immersive media such as 360-degree visualizations show strong educational potential [22] with hybrid AR–360-degree approaches being used to support remote collaboration and access [13, 29]. Despite research on mobile XR and outdoor learning, prior work largely treats user location as fixed. The influence of a learner's physical proximity to the represented site, ranging from remote to on-site use, on learning experience and outcomes in mobile XR applications remains unexplored. It is therefore important to further investigate the influence of spatial proximity, and context on user perception.

3 Design Process

In the following, we will describe the design process of our work, including an informal pre-study as well as a qualitative and quantitative between-subject user study with upper school classes at the Wendelstein observatory.

3.1 Formative Pre-Study and Concept

To investigate how physical location influences the experience of an educational mobile XR application, we identified two primary conditions: *remote* and on-site (*summit*). During informal pre-study interviews with 18 mountain visitors, we identified a third intermediate condition: the *plateau*, which is reachable entirely by cable car. While physically close to the observatory, users on the *plateau* are not directly at the facility. Some visitors or their partners reported difficulty hiking from the *plateau* to the *summit*, suggesting that the *plateau* could be an important location to bridge observatory access through XR, but may also introduce perceptual mismatches due to the incomplete physical context. Therefore, beyond the capacity constraints of the observatory, additional barriers such as physical distance and health-related limitations further restrict participation. Interviews also indicated that visitors were particularly interested in star imagery, the observatory's research and technology, the surrounding view and history, as well as having free exploration without requiring downloads. Motivated by these findings and approved by the ethics committee, we developed a prototype XR application to support these interests and evaluated it across the three proximity levels to address the following research question:

RQ How does the *physical proximity* affect the learning experience during the interaction with an educational mobile XR experience?

To examine the effects of proximity, we conducted a mixed-methods user study using a one-factor, three-level between-subjects design (*remote*, *plateau*, *summit*). Each condition was deployed in a separate class session, therefore, the conditions are confounded with day-level factors such as weather, time pressure, and exertion. As a result, our analyses focus on field-realistic proximity regimes rather than isolating proximity as a single causal factor. We measured mental load, presence, motivation, perceived access, and learning outcomes through standardized questionnaires and custom items in both English and the local language. Additionally, we collected qualitative observations of participant interaction during the study.

3.2 Apparatus

We developed a mobile web-based XR application to ensure broad device compatibility and access. The application was implemented using HTML and PHP with a SQLite3 database and built on A-Frame for rendering interactive XR content in mobile browsers. The participants were distinguished by using a session ID while directly anonymizing the data. The application included several interactive 3D elements related to the observatory. Users could explore a rotatable and zoomable 3D CAD model of a telescope with annotations explaining its technical components. In addition, two telescopes were implemented using 3D scans captured and processed by the *Deutsches Museum Digital*[1]. An interactive sky view allowed users to drag a virtual telescope across the sky: At physically accurate celestial positions, images of galaxies and stars prior captured by the observatory were displayed along with contextual information. Further, a drop-down menu gave the possibility to see the entire environment as the surrounding galaxy in the correct position in different wavelengths. The visual representation of the environment was adapted to the user's physical location. When users were on site, the surroundings were shown using the smartphone camera in AR. At different locations, immersive 360-degree images of the *plateau* and *summit* were used to provide a consistent experience with the application content being available across all conditions. The entire application was developed in close collaboration with experts from the fields of physics and education. Examples of the application are shown in Figure 1.

3.3 Procedure

Prior to the study, written informed consent was obtained from all participants and one of their legal guardians. The study was conducted in the context of a school field trip, during which three school classes traveled to the assigned study locations. At each location, participants received a brief explanation of the study procedure and accessed the mobile XR application by scanning a QR code with their own smartphones. Consent was then confirmed again digitally within the application. Participants first completed a pre-questionnaire assessing age, gender, and prior experience. They then freely explored the application and interacted with all available content at their own pace. Upon completion, a pop-up window prompted participants to answer the post-questionnaire including a self-implemented 10-item knowledge quiz regarding the application content. The participants were then officially released from the study. The entire study session lasted approximately 20 minutes per participant group.

[1]Scan: Deutsches Museum/Claus Henkensiefken, CC BY-SA 4.0, https://digital.deutsches-museum.de/en/, Last Accessed: March 10, 2026

3.4 Participants

In the study, a total of 35 healthy upper grade students of three classes participated on different days voluntarily, without receiving reimbursement and with the option to withdraw from the study at any time: 14 (6 women and 8 men) 18-year-old students participated *remotely*, 14 (13 women, 1 preferred not to disclose) aged between 18 and 19 ($Mean = 18.1$, $SD = 0.27$) on the *plateau*, as well as 7 (2 women, 5 men) 18-year-old on the *summit*. We also asked if the participants had already been to the mountain before the *remote* (10 yes, 3 no, 1 unsure), *plateau* (7 yes, 7 no), or the *summit* (5 yes, 1 no, 1 unsure) condition.

3.5 Analysis

We analyzed our data using Ordinal Regression Models with CLM from the `ordinal` R package as suggested by Christensen [7]. To estimate the mean response, we used Bonferroni-corrected Estimated Marginal Means (EMMs) as proposed by Searle et al. [26] using the `emmeans` package.

4 Results

In this section, we report the results of our in-the-wild quantitative and qualitative study: While quiz performance of the 10 questions did not differ significantly between conditions ($M = 5.97$, $SD = 1.46$), we observed effects of context-dependent proximity on mental workload, presence, motivation, and perceived access.

4.1 Questionnaires

We assessed **mental workload** using the Raw NASA-TLX [10]. While no significant differences were observed for the overall workload score, the effort subscale (Figure 2a) revealed a significant effect ($\chi^2(2) = 6.51,\ p < .05$), with *plateau* rated higher than *remote* ($p < .05$). Similarly, the frustration subscale (Figure 2b) showed a significant difference ($\chi^2(2) = 6.42,\ p < .05$), with higher ratings for *plateau* compared to *summit* ($p < .05$). Perceived **presence** was measured using the igroup presence questionnaire (IPQ) [24]. For spatial presence (Figure 2c) we found significant effects ($\chi^2(2) = 6.67,\ p < .05$), but also for overall presence ($\chi^2(2) = 8.60,\ p < .05$) (Figure 2d), with *summit* receiving higher ratings than *remote* in both cases ($p < .05$). We evaluated **motivation** and **perceived access** using custom questionnaire items (7-point Likert scale, 1: Strongly disagree, 7: Strongly agree). Motivation (Figure 2e) differed significantly across conditions ($\chi^2(2) = 6.93,\ p < .05$), with *summit* rated higher than *plateau* ($p < .05$). Perceived access (Figure 2f) also showed a significant effect ($\chi^2(2) = 6.87,\ p < .05$), with *summit* rated higher than both *plateau* and *remote* ($p < .05$).

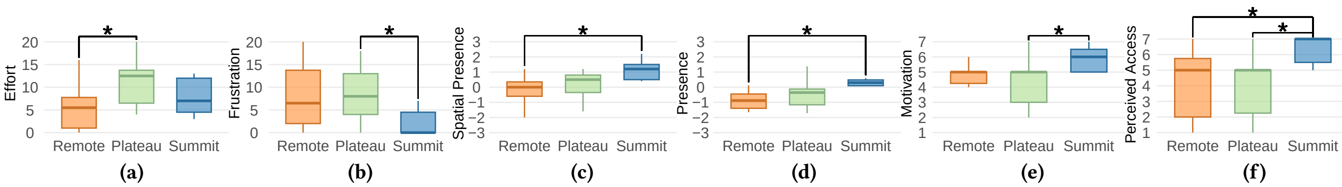

Figure 2: Box plots of the values showing significance (p<.001: ∗ ∗ ∗, p<.01: ∗∗, p<.05: ∗), including the effort (a), frustration (b), spatial presence (c), overall presence (d), motivation (e), and perceived access (f).

4.2 Qualitative Notes

Alongside the questionnaires, we collected qualitative field notes on environmental conditions and participant behavior during the three study mornings. In the *remote* condition, it was rainy, quiet, and approximately 8 °C. Participants were motivated, showed some confusion about the need to physically turn with the smartphone to explore the environment, and occasionally helped each other when struggling. At the *plateau*, conditions were cloudy, windy, and colder (2–4 °C). Participants frequently supported each other when encountering difficulties and often alternated their attention between the application and the real telescope nearby. Toward the end, participants hurried to finish due to the cold. At the *summit*, weather conditions were similarly cold and windy. Participants quickly understood the application and worked mostly independently, but again completed the tasks rapidly, likely influenced by the low temperature.

5 Discussion

Our findings show that physical proximity to an inaccessible site including the associated environmental factors significantly shapes the experiential aspects of mobile XR use, while having no measurable effect on the quiz questions. Quiz performance did not differ between conditions, aligning with prior work showing that XR can support learning even in *remote* settings [6, 22]. This could be an indication that learners were able to acquire factual information equally independent of physical proximity.

In contrast, context-dependent proximity influenced user experience. Participants at the *summit* reported significantly higher spatial and overall presence, and perceived access than those in the *remote* condition. The results indicate that being in a shorter physical distance amplifies not only the sense of being there but also the feeling of being closer to actually visiting it. As a result this could also have led to the participants working on their own instead of talking to each other. Mental workload revealed a differentiated pattern. While overall workload remained stable, participants at the *plateau* reported higher effort than at the *remote* location, but also increased frustration compared to the *summit*. This intermediate condition appears to represent a cognitively demanding state in which users could see the observatory but were not close enough to feel satisfied with the experience. This may also lead to decreased motivation and perceived access compared to the *summit* condition, aligning with earlier findings on the role of authentic context in improving perceived relevance and engagement [25]. Further, this was also supported by the observations of increased peer support and frequently switching between the application and the real telescope at the *plateau*. Also, the environmental factors could have influenced interaction behavior across all on-site conditions. Similar cold and windy weather led participants at the *plateau* and *summit* to complete the study more quickly. Still, presence and motivation remained highest at the *summit*. This suggests that proximity effects on experience were robust even under less comfortable conditions. We further argue that the hike from the *plateau* to the *summit* could have due to the physical movement positively influenced the experience [21] and thereby also the perception of the application.

Overall, the findings indicate that physical proximity functions despite environmental conditions as an experiential amplifier in mobile XR: it can enhance presence, motivation, and perceived access without necessarily increasing immediate learning outcomes. Thereby, especially in the *plateau* condition the confusion of presence and between real and virtual content seem to worsen the experience. These results are a first indicator that highlights the importance of considering context-dependent proximity as a key design and evaluation dimension for XR systems aimed at making inaccessible places meaningfully available.

6 Limitations and Future Work

Regarding study scope, participant numbers varied across conditions due to the outdoor deployment and the school-based participant group. While this resulted in an uneven distribution across conditions, it enabled the study to be conducted in a realistic, ecologically valid setting. In this context, the study design, field-based implementation and environmental conditions may have shaped the observed outcomes. However, these choices were essential for capturing authentic use contexts rather than tightly controlled laboratory behavior. The XR application employed static imagery instead of video or live streams, reflecting practical considerations related to data volume and privacy. This design choice ensured reliable performance and accessibility in situ, while opening opportunities for future work to explore richer media formats and complementary technologies beyond mobile XR. Finally, the evaluation emphasized experiential measures such as motivation, presence, and perceived access. Although a short quiz was included to assess content understanding, it provides only an initial indication of knowledge acquisition. Future studies could extend this work by incorporating more comprehensive and longitudinal learning assessments with larger and more diverse participant groups. Finally, we want to highlight the importance of remote and intermediate learning applications in terms of accessibility, motivating future research to improve their effectiveness.

7 Conclusion

This study demonstrates that physical proximity to an inaccessible site including environmental factors can significantly influence the user experience of mobile XR, affecting presence, motivation, perceived access, and aspects of mental workload. While quiz results did not differ across conditions, being directly in front of the observatory enhanced experiential engagement and strengthened the connection between virtual content and real-world context. These findings highlight context-dependent physical proximity as an important design dimension for XR systems and suggest that proximity-aware adaptations can make inaccessible places feel more meaningful and engaging for learners.

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