Cross-Context Evaluation of an Indoor–Outdoor AR Navigation System in a University Campus Environment

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***Abstract*—This paper presents a comparative evaluation of a mobile augmented reality (AR) navigation application designed for both indoor and outdoor university environments. Building on a previously validated system for indoor guidance, the current study extends the deployment to outdoor campus spaces without relying on GPS or additional infrastructure. Using visual positioning and spatial anchors, the same application provides real-time AR cues and audio instructions to support wayfinding across different spatial contexts. The principal aim of this study is to determine whether a unified AR navigation system can deliver a consistent, infrastructure-free user experience in both indoor and outdoor university environments. A within-subjects study was conducted with 256 university students who completed both indoor and outdoor navigation tasks. Usability and user acceptance were assessed using the System Usability Scale (SUS) and constructs from the Technology Acceptance Model (TAM). Results revealed consistent user experience across both contexts, with no statistically significant differences in perceived intuitiveness, usefulness, engagement, behavioral intention to reuse, or localization accuracy. A significant difference was found only in perceived AR content loading speed, which was rated slightly higher indoors. These findings demonstrate the feasibility of a unified AR navigation system for academic campuses and provide practical insights into its scalability and user-centered design.**

***Keywords*—Augmented reality; hybrid navigation; spatial computing; usability testing; indoor-outdoor contexts; ARCore; higher education**

I. INTRODUCTION

Indoor navigation remains a significant challenge in large, unfamiliar environments such as hospitals, airports, and university campuses. Traditional wayfinding methods—including signage, printed maps, and kiosks—often fall short in addressing the spatial complexity and dynamic layouts of such settings [1]. In academic institutions, students and visitors frequently struggle to locate classrooms, offices, or facilities within multi-story buildings or across expansive outdoor areas. Augmented Reality (AR) has emerged as a promising solution by superimposing navigational cues—such as arrows, labels, and landmarks—onto the real-world view through mobile devices, enhancing spatial cognition and real-time orientation [2]. Navigating unfamiliar academic campuses, particularly during orientation periods, open days, or student admissions, is a recurring challenge that affects thousands of users each academic year. AR-based navigation tools offer an accessible, real-time solution that does not require technical training, printed maps, or assistance from staff—making them ideal for practical deployment in higher education settings.

While AR navigation systems for outdoor use have benefited from reliable GPS signals and integration with digital mapping services [3], indoor environments present unique technical constraints. GPS signals tend to degrade or become unavailable indoors, requiring alternative technologies such as Simultaneous Localization and Mapping (SLAM), Visual Positioning Systems (VPS), and visual-inertial odometry [4]. These differences in spatial and technical conditions suggest that the user experience may vary considerably between indoor and outdoor AR navigation contexts. However, few studies have examined this comparative dimension directly.

This study addresses the following research question:

Can a single mobile AR navigation system provide a seamless and equally usable experience across both indoor and outdoor university environments, without relying on GPS or additional infrastructure? Answering this question can inform future designs of scalable, user-friendly AR navigation systems for education and beyond.

Recent advances in mobile AR platforms—such as Apple ARKit and Google ARCore—have enabled increasingly accurate, infrastructure-free AR navigation solutions across domains including education, healthcare, and retail. These frameworks provide core functionality for markerless tracking, real-time camera pose estimation, and rendering of 3D navigation overlays [5], [6]. Studies report promising results for both usability and technical feasibility. For instance, Yamamoto et al. implemented an AR indoor navigation app using BLE beacons in a university setting, achieving over 70% user satisfaction and stable guidance performance [6].

Despite growing interest, university campuses remain relatively underexplored in AR navigation research—particularly in terms of integrated indoor–outdoor deployment. Most existing studies either evaluate AR in confined indoor settings or focus solely on outdoor AR guidance, often under pilot conditions or with small sample sizes [2], [7]. Moreover, many systems rely on infrastructure such as BLE beacons or GPS, limiting scalability. Our work addresses these limitations by proposing and evaluating a unified, infrastructure-free system that supports consistent AR-based navigation across spatial contexts. This lack of cross-context evaluation limits our understanding of how environmental factors influence usability, responsiveness, and user acceptance of AR-based wayfinding solutions.

The present study addresses this gap by extending a previously developed mobile AR navigation system [8]—initially tested for indoor guidance—to a campus-wide outdoor scenario, followed by a comparative evaluation. The application is implemented using Unity 3D and the ARway SDK and supports both Android and iOS platforms via ARCore and ARKit. Importantly, the system operates without dedicated infrastructure (e.g., BLE beacons or markers), using camera-based localization and cloud-based spatial anchors instead. Users initialize navigation by scanning a QR code at a known location—either indoor or outdoor—and follow AR overlays and audio cues that provide dynamic, step-by-step guidance.

This paper offers two main contributions: (1) it demonstrates the scalability and adaptability of a mobile AR navigation system across indoor and outdoor university environments, and (2) it presents a comparative analysis of user experience across these contexts, based on a large-scale user study. The evaluation framework includes metrics such as perceived usability, intuitiveness, system responsiveness, engagement, and behavioral intention to reuse the app. These dimensions are quantified using the System Usability Scale (SUS) [9] and constructs from the Technology Acceptance Model (TAM) [10], allowing for hypothesis-driven analysis of how spatial context affects AR navigation acceptance. The findings extend prior indoor-only results and contribute practical insights for designing seamless AR wayfinding systems suitable for real-world educational environments.

The remainder of this paper is organized as follows: Section II reviews the relevant literature on AR-based indoor and outdoor navigation systems; Section III details the system design and methodology; Section IV presents the results of the comparative user study; Section V discusses the findings in relation to prior work; and Section VI concludes with insights and future research directions.

II. Related Work

A. Outdoor AR Navigation Systems

Augmented Reality (AR) has gained significant traction as a tool for spatial navigation in both indoor and outdoor environments. AR enhances spatial cognition by overlaying digital cues—directional arrows, labels, or visual landmarks—onto the user’s real-world view, improving situational awareness and wayfinding performance [1]. Outdoor AR navigation systems are more established due to their reliance on GPS, digital maps, and compass-based orientation [11]. For example, Huang et al. [12] developed an AR pedestrian navigation prototype integrating GPS and computer vision to display route information in real-time street views. Commercial map applications such as Google Maps have also adopted AR for walking navigation, indicating a rise in public familiarity with AR-based outdoor guidance. However, these systems rely heavily on GPS and are limited in environments with signal loss or visual occlusions.

B. Indoor AR Navigation: Infrastructure Challenges

Indoor AR navigation, however, presents unique challenges stemming from unreliable or unavailable GPS signals. To address this, various positioning strategies have emerged: BLE (Bluetooth Low Energy) beacons [6], Wi-Fi fingerprinting [4], visual marker systems, and vision-based SLAM (Simultaneous Localization and Mapping) techniques [13]. These alternatives often require specialized infrastructure or calibration. For instance, Nguyen and Park [14] deployed a BLE-based AR guidance system in a shopping mall, achieving high positional accuracy and user satisfaction. Similarly, Gupta et al. [4] used a hybrid of Wi-Fi fingerprinting and SLAM in a hospital environment, attaining room-level localization and effective navigation performance. While effective, these solutions require infrastructure deployment (e.g., BLE beacons), limiting scalability and generalizability across different buildings or institutions.

C. Advances in Markerless AR Navigation

Recent mobile AR development frameworks—such as Apple’s ARKit and Google’s ARCore—have enabled more accurate, markerless tracking capabilities via SLAM and visual-inertial odometry [15],[16]. Rossi et al. [5] used ARKit to build an indoor navigation prototype that resulted in a 35% reduction in wayfinding time. Chen et al. [17] employed ARCore for multi-floor campus navigation, leveraging persistent cloud anchors and reporting an 81% ease-of-use rating. These tools have become foundational in AR navigation research by enabling infrastructure-free guidance with stable content anchoring and route overlays. Yet, most deployments remain confined to either indoor or outdoor use, lacking evaluation across both contexts with the same system.

Localization precision remains a key factor in AR navigation. Outdoors, GPS typically provides 5–10 meter accuracy, but AR systems often require finer granularity to align virtual objects meaningfully with physical spaces. Visual Positioning Systems (VPS), such as Google’s AR VPS, supplement GPS by comparing camera views to geo-referenced imagery [12]. Indoors, BLE beacons can offer ~3–5 meter accuracy, while UWB (Ultra-Wideband) radio systems can achieve sub-meter precision. Yamamoto et al. [6] used over 100 BLE beacons in a university building to power their AR app, noting limitations such as signal decay and interference in crowded spaces. Alternatively, QR codes or fiducial markers can serve as anchor points, offering high-precision initialization and periodic re-localization to mitigate SLAM drift—a strategy employed in the current system.

D. Hybrid and Cross-Context Systems

To ensure seamless indoor–outdoor transitions, hybrid approaches have emerged. Fernandez et al. [7] proposed a GPS emulation mechanism using cloud-based AR maps to support campus-scale navigation. Qi et al. [18] developed a hybrid ARCore-based solution using visual-inertial odometry and cloud anchors, demonstrating improved spatial tracking across both indoor and outdoor contexts. These systems still face challenges related to lighting variations, visual occlusion, and UI continuity during environment transitions, but they represent meaningful steps toward unified AR navigation experiences, as shown in [19] and [20]. Nevertheless, these studies are either experimental or simulate GPS using cloud anchors; they stop short of large-scale user evaluations in naturalistic academic settings.

E. User Experience and Acceptance

Accurate localization is only one facet; usability and user experience are equally critical. Many studies use the System Usability Scale (SUS) and the Technology Acceptance Model (TAM) to quantify user perceptions. SUS is a 10-item instrument that yields a usability score between 0 and 100 [9]. Chen et al. [17] reported a SUS score of 74 in a campus navigation scenario, and Sato et al. [21] achieved a score of 76 in a museum-based AR guide. These results suggest generally favorable usability perceptions in both educational and cultural settings.

TAM provides a theoretical lens to understand user adoption by evaluating perceived usefulness, ease of use, and behavioral intention [10]. In AR navigation contexts, perceived ease of use refers to how effortlessly users can interpret and follow AR cues, while perceived usefulness reflects whether the system enhances their navigation performance. Kwok et al. [22] extended TAM to include enjoyment and found that higher enjoyment correlated with greater acceptance of AR navigation in a university environment. The study also noted the role of social visibility—users may hesitate to use AR interfaces in public due to perceived awkwardness, a relevant consideration for campus-wide deployment. Our current study extends this by collecting SUS and TAM responses in both indoor and outdoor conditions using the same AR system, enabling direct comparison.

F. Technical Factors Affecting Usability

Technical factors also influence adoption. Users expect AR systems to be responsive, visually stable, and intuitive. Lagging overlays, jittery directional arrows, or poor contrast in bright sunlight can degrade the experience [17], [21]. Several studies report that system responsiveness is a strong predictor of SUS scores. In our prior study, responsiveness and tracking stability were among the most significant factors contributing to perceived usability. Zhao et al. [23] demonstrated that using an AR headset equipped with high-performance sensors yielded an 88% navigation success rate but caused user fatigue—underscoring the trade-offs between accuracy and usability. Our system, unlike high-performance AR headsets, achieves stable performance using only consumer smartphones, balancing usability and accessibility.

G. AR Navigation in Educational Settings

Beyond navigation efficiency, AR has been shown to reduce cognitive load and enhance users' ability to form cognitive maps. Qiu et al. [1] reported that AR improved user confidence and spatial memory, even when it did not significantly reduce travel time compared to traditional 2D maps. Ahn et al. [24] found that AR guidance in a hospital led to faster learning of spatial layouts and a high initial orientation success rate of 86%. These qualitative benefits align with the TAM concept of perceived usefulness and highlight AR's role not only in performance but in experiential engagement.

Research in educational settings remains relatively sparse but is growing. AR navigation aligns with smart-campus initiatives, offering new students or visitors accessible guidance through complex academic environments. Fernandez et al. [7] and Yamamoto et al. [6] deployed their systems in real campus scenarios with participant samples exceeding 50 users. Our prior study, with 256 participants, remains one of the most extensive in this domain. However, most existing works evaluate either indoor or outdoor AR usage in isolation. Little is known about how users perceive and interact with AR systems that transition across spatial contexts [25].

In summary, the literature shows steady progress in AR navigation across diverse settings. However, notable gaps remain: (1) few comparative evaluations of indoor versus outdoor AR navigation using the same system; (2) limited research in education-specific deployments at scale; and (3) scarce longitudinal studies on sustained adoption. This paper addresses the first of these by evaluating a hybrid AR navigation system deployed in both indoor and outdoor areas of a university campus. Through an empirical comparison grounded in SUS and TAM frameworks, the study aims to generate insights into how spatial context influences usability and user acceptance in real-world academic environments. This paper fills a key gap by offering one of the first comparative, infrastructure-free, cross-context AR navigation evaluations in a university campus, involving over 250 participants.

III. METHODOLOGY

This study builds on a previously published evaluation of an AR-based indoor navigation application [8], extending the investigation to outdoor university campus spaces. To preserve continuity while enabling comparative insight, the methodology replicates the core structure of the initial research while adjusting the deployment context and data collection accordingly.

A. Research Design and Context

We adopted a user-centered, exploratory methodology integrating system deployment with empirical usability evaluation. The same AR application, previously tested indoors, was adapted and redeployed in selected outdoor areas of the university campus, using the same visual positioning and spatial anchoring approach (SLAM + VPS). Unlike traditional GPS-based outdoor navigation, our system does not rely on GNSS signals, allowing consistent performance across both spatial environments.

A within-subjects experimental design was employed, with each participant completing two navigation tasks—one indoors and one outdoors. The study retained the System Usability Scale (SUS) and the Technology Acceptance Model (TAM) as its core evaluative frameworks, consistent with the prior research.

B. Description of the AR Navigation Application

To extend the functionality of the indoor AR navigation system into outdoor campus settings, the same mobile application was adapted without relying on GPS or external sensors. Instead, it continues to use visual-inertial localization based on cloud-anchored spatial mapping, implemented via the ARway SDK and Unity 3D. The navigation experience was redesigned to suit open environments while maintaining consistency in interface and interaction style across both indoor and outdoor contexts.

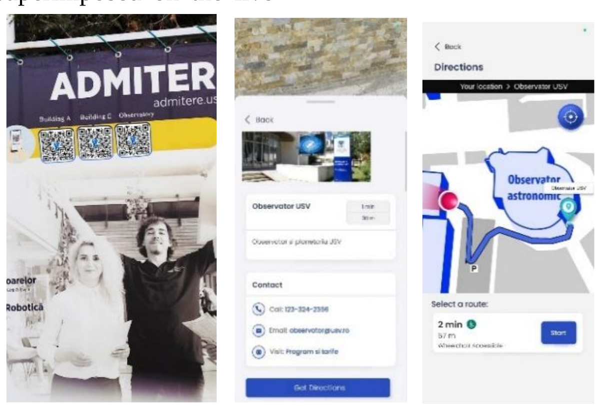
Navigation begins when the user scans a designated QR code positioned on outdoor campus signage, such as the official admissions board located at the entrance to campus facilities [Fig. 1(a)]. This QR code acts as an initialization anchor, aligning the digital scene with the real-world coordinate system to enable precise overlay of AR guidance elements. Once initialized, the user is presented with a location selection interface, from which they can choose a point of interest—such as the university's astronomical observatory.

Upon selecting a destination, the application displays a detailed preview including a representative photo, contact information, and a "Get Directions" button [Fig. 1(b)]. Tapping this option generates a contextual route preview, where users can see the estimated walking time and total distance to the target [Fig. 1(c)]. Notably, the app also flags whether the suggested route is wheelchair accessible, ensuring inclusivity in the wayfinding experience.

Once navigation is initiated, the application renders the route as a sequence of 3D arrows superimposed on the live camera feed. These directional cues update dynamically as the user moves through the campus, ensuring accurate step-by-step guidance [Fig. 2(a)]. In parallel, textual instructions and optional audio prompts provide redundancy, enhancing usability in varying light and noise conditions [Fig. 2(b)]. The interface design remains minimalistic and accessible, with large tap areas, clean typography, and consistent iconography.

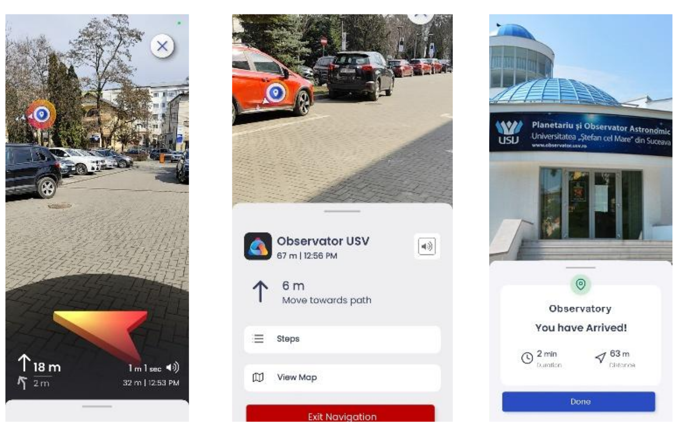
The final phase of the navigation process—approaching the destination—is supported by persistent AR labels and markers positioned in the user's field of view. These indicators signal proximity to the target and offer visual confirmation upon arrival [Fig. 2(c)]. As with the indoor scenario, no GPS or BLE infrastructure is needed; the entire navigation experience is powered by camera-based tracking and spatial anchors, making it scalable and deployable without physical modifications to the environment.

This outdoor adaptation demonstrates that the same infrastructure-free AR system can offer seamless wayfinding across spatial contexts, guiding users from common entry points on campus to specific buildings or functional areas with minimal friction. The user experience, interaction logic, and technological backbone remain consistent with the previously evaluated indoor deployment, ensuring methodological continuity for comparative analysis.



(a) QR code scanning. (b) Location details. (c) Location path.

Fig. 1. User interface and interaction (I)



(a) Visual cues (b) Additional details. (c) Arrival confirmation.

Fig. 2. User interface and interaction (II)

C. Participant Profile and Study Duration

A total of 256 students from Ștefan cel Mare University of Suceava participated in the comparative study. This participant pool mirrors the one from the initial indoor evaluation. Most were enrolled in the first (70.7%) or second (26.2%) year of undergraduate studies, with the remaining (3.1%) from higher years or master's programs. This demographic ensured low prior familiarity with campus routes, particularly outdoor connectors between buildings.

Participants were required to have AR-capable smartphones. Of the total, 153 had prior exposure to AR applications, while 103 had none. This variation supported robust evaluation of both usability and adoption potential.

D. Experimental Setup and Testing Procedure

Each participant completed two navigation tasks using the same AR app: one indoor, one outdoor. The order was counterbalanced. In both scenarios, QR codes marked the navigation start points. Users selected a destination from the on-screen list and followed AR cues to reach the target location. Outdoor destinations included pedestrian pathways between faculty buildings. Navigation took 2–3 minutes per task.

The application provided continuous AR guidance without requiring server connectivity. No external assistance was offered, simulating real-world use. After completing both routes, participants filled out a post-task questionnaire on their own device. Each session lasted ~15 minutes and was conducted individually during daytime under stable weather conditions.

E. Research Hypotheses

The study formulated the following hypotheses for comparative evaluation:

- H1: No significant difference in perceived ease of use between indoor and outdoor conditions.
- H2: Perceived usefulness is higher indoors due to complex spatial layouts.
- H3: System responsiveness predicts SUS scores across both conditions.
- H4: SUS scores do not differ significantly across environments.
- H5: Behavioral intention to reuse is positively associated with perceived usefulness.
- H6: Outdoor environmental factors (e.g., lighting, visual features) may influence responsiveness perception.

The study was reviewed and approved by the Ethics Committee of Ștefan cel Mare University of Suceava. All participants were informed about the nature and purpose of the research, and informed consent was obtained prior to their involvement. Data collection adhered to institutional guidelines on ethical conduct, privacy, and voluntary participation.

The following section presents the results of the comparative evaluation, focusing on key user experience indicators measured across indoor and outdoor navigation scenarios.

IV. RESULTS

A. Hypothesis 1 (H1): There is no Statistically Significant Difference between users' Perception of the Application's Intuitiveness in Indoor Versus Outdoor Navigation Scenarios

The first hypothesis aimed to explore whether users perceive the augmented reality (AR) navigation application as equally intuitive in both indoor and outdoor university environments. According to user-centered design principles and the Technology Acceptance Model (TAM), intuitiveness plays a critical role in influencing user engagement and perceived usability across different contexts.

To test this hypothesis, a paired-samples t-test was conducted, comparing two questionnaire items:

- "How intuitive did you find the indoor navigation mode?"
- "How intuitive did you find the outdoor navigation mode?"

Both variables were measured on a 5-point Likert scale (1 = Not at all intuitive, 5 = Very intuitive). Descriptive statistics are presented in Table I, showing nearly identical means for both contexts: indoor ($M = 3.83$, $SD = 0.97$) and outdoor ($M = 3.83$, $SD = 1.00$), suggesting a uniform perception of intuitiveness across environments.

TABLE I. DESCRIPTIVE STATISTICS FOR PERCEIVED INTUITIVENESS IN INDOOR VS OUTDOOR SCENARIOS

Variable	Mean	Std. Deviation	N
Indoor Navigation Intuitiveness	3.83	0.97	256
Outdoor Navigation Intuitiveness	3.83	1.00	256

The results of the t-test revealed no statistically significant difference between the two means: $t(255) = -0.066$, $p = 0.947$ (see Table II). The mean difference was minimal (−0.004), reinforcing the conclusion that users found the application equally intuitive regardless of whether it was used indoors or outdoors.

TABLE II. PAIRED-SAMPLES T-TEST FOR INTUITIVENESS SCORES IN INDOOR VS OUTDOOR CONTEXTS

Variable Pair	Mean Difference	t	df
Indoor vs. Outdoor Intuitiveness Scores	−0.004	−0.066	255

These findings support the hypothesis that intuitiveness is perceived consistently across navigation environments. This consistency may reflect the application's cohesive design and interface behavior across contexts, suggesting that once familiarized with the system, users can transfer their expectations and interactions seamlessly between indoor and outdoor use. Fig. 3 illustrates the comparison between students perceived intuitiveness of the AR application during indoor and outdoor navigation. As shown, the mean scores for both scenarios are virtually identical (M_indoor = 3.83; M_outdoor

= 3.83), indicating a consistent user experience across environments.

A paired-samples t-test confirmed that this difference is not statistically significant (t(255) = −0.066, p = 0.947). These findings suggest that the application's intuitive design was equally effective in guiding users regardless of the spatial context, supporting its usability in both structured (indoor) and open (outdoor) campus environments.

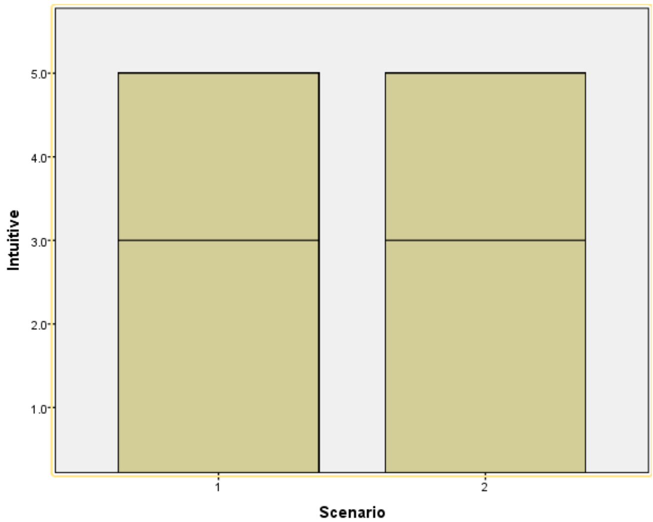


Fig. 3. Mean perceived intuitiveness of the AR application during indoor and outdoor navigation scenarios. Error bars are not displayed due to negligible variation. No significant difference was observed between conditions (p = 0.947).

This result is particularly relevant for the design of hybrid AR navigation solutions in academic settings, where continuity of experience across spatial contexts (e.g., classroom buildings, campus pathways) enhances usability and adoption.

B. *Hypothesis 2 (H2): The Application is Perceived as More Useful in Indoor Navigation than in Outdoor Navigation*

The second hypothesis investigated whether users perceive the augmented reality (AR) navigation application as more useful in indoor environments (e.g., corridors, classrooms) than in outdoor settings (e.g., between campus buildings). This assumption stems from the idea that indoor environments are typically more challenging for spatial orientation due to occlusion, lack of clear landmarks, and complex layouts, which AR tools are specifically designed to mitigate.

To examine this hypothesis, a paired-samples t-test was conducted between the following two items:

- "I believe this application significantly improves my ability to orient myself within campus buildings."
- "I believe this application significantly improves my ability to orient myself in exterior campus spaces."

Both items used a 5-point Likert scale (1 = Strongly disagree, 5 = Strongly agree). Descriptive statistics are presented in Table III, showing slightly higher scores for indoor utility (M = 4.20, SD = 0.91) compared to outdoor (M = 4.11, SD = 0.94).

TABLE III. DESCRIPTIVE STATISTICS FOR PERCEIVED UTILITY IN INDOOR VS. OUTDOOR CONTEXTS

Variable	Mean	Std. Deviation	N
Indoor Navigation Utility	4.20	0.91	256
Outdoor Navigation Utility	4.11	0.94	256

A paired-samples t-test revealed that this difference was not statistically significant, t(255) = 1.704, p = 0.090 (see Table IV). The mean difference of +0.086 indicates a slight preference for indoor use, but this was insufficient to support the hypothesis at the conventional $\alpha = 0.05$ level.

TABLE IV. PAIRED-SAMPLES T-TEST FOR PERCEIVED UTILITY SCORES IN INDOOR VS. OUTDOOR CONTEXTS

Variable Pair	Mean Difference	t	df
Indoor vs. Outdoor Utility Scores	+0.086	1.704	255

While the data suggest a marginal trend favoring indoor use in terms of perceived utility, the lack of statistical significance indicates that users view the application as equally beneficial for both indoor and outdoor navigation. This result may reflect the versatility and adaptability of the application interface and the consistency of user experience across spatial contexts.

The chart presented in Fig. 4 illustrates the distribution of perceived utility scores (Perception_Utility) across two usage scenarios: indoor (1) and outdoor (2). This visualization is directly relevant to Hypothesis 2 (H2), which proposed that users would perceive the application as more useful in indoor navigation contexts (e.g., hallways, classrooms) than in outdoor settings (e.g., between buildings). However, the nearly identical heights of the bars suggest that perceived utility is very similar across both scenarios.

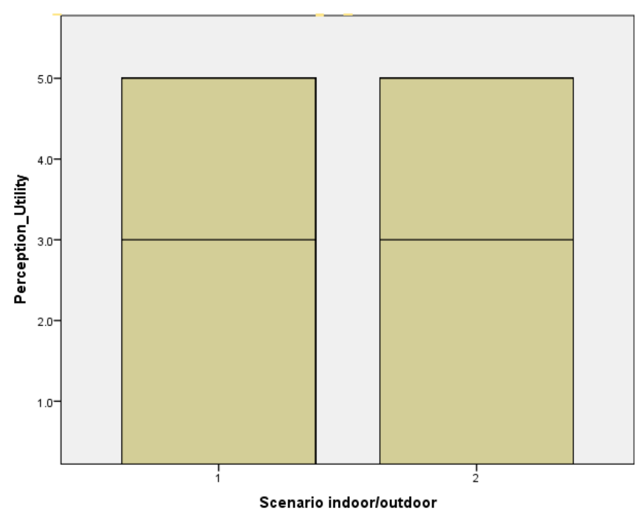


Fig. 4. Mean perceived utility scores across indoor (1) and outdoor (2) navigation scenarios. The near-identical column heights indicate similar user evaluations in both contexts, consistent with the non-significant statistical difference.

This graphical similarity aligns with the results of the paired-samples t-test, which revealed no statistically significant difference between the two conditions (M_indoor = 4.20, M_outdoor = 4.11, p = 0.090). Although there was a slight numerical advantage for indoor use, the difference was insufficient to support H2 at the conventional significance level.

These findings indicate that users consider the application to be equally effective for orientation and navigation tasks in both spatial contexts.

These findings provide important insights for developers aiming to scale AR-based navigation tools across campus-wide deployments, as both environments appear equally receptive to technological support in orientation tasks.

C. Hypothesis 3 (H3): The Navigation Experience is Perceived as More Engaging in Indoor Settings than in Outdoor Settings

The third hypothesis examined whether users find the augmented reality (AR) navigation experience more stimulating or engaging when used indoors, as opposed to outdoors. Indoor AR experiences may be enhanced by the presence of walls, corridors, and structured spaces that can provide more immersive contextual cues, whereas outdoor environments may dilute these effects due to broader visual openness and variable lighting.

To assess this, participants responded to two parallel questionnaire items:

- "How engaging or stimulating did you find the indoor navigation experience?"
- "How engaging or stimulating did you find the outdoor navigation experience?"

Responses were measured on a 5-point Likert scale (1 = Not at all, 5 = Very much). Descriptive statistics, displayed in Table V, show nearly identical mean scores: indoor (M = 4.02, SD = 0.92) and outdoor (M = 4.04, SD = 0.95), suggesting an overall balanced experience across contexts.

TABLE V. DESCRIPTIVE STATISTICS FOR PERCEIVED ENGAGEMENT IN INDOOR VS. OUTDOOR SCENARIOS

Variable	Mean	Std. Deviation	N
Indoor Navigation Engagement	4.02	0.92	256
Outdoor Navigation Engagement	4.04	0.95	256

A paired-samples t-test confirmed that this difference is not statistically significant, t(255) = −0.409, p = 0.683 (see Table VI). The very small mean difference (−0.02) indicates no real practical disparity in how engaging the navigation experience was perceived across settings.

TABLE VI. PAIRED-SAMPLES T-TEST FOR NAVIGATION EXPERIENCE ENGAGEMENT

Variable Pair	Mean Difference	t	df
Indoor vs Outdoor Engagement Scores	−0.020	−0.409	255

The results of Hypothesis 3 suggest that users found the navigation experience equally engaging in both indoor and outdoor environments. This outcome may reflect the consistent visual and interaction design of the AR application across contexts, or it may point to the novelty of the technology itself as a key driver of engagement, independent of location.

From a design perspective, this reinforces the value of cohesive AR experiences that deliver similar affective impact regardless of spatial constraints or environmental variables.

D. Hypothesis 4 (H4): The Application Loads Faster and more Smoothly in Indoor Environments than in Outdoor Environments

The fourth hypothesis examined whether users perceived the augmented reality (AR) application as performing better—in terms of content loading speed and responsiveness—indoors compared to outdoors. This hypothesis is grounded in the assumption that indoor environments often provide more stable Wi-Fi connectivity, reduced glare, and consistent lighting, which may facilitate faster AR marker recognition and content rendering.

To evaluate this, a paired-samples t-test was conducted comparing responses to the following items:

- "How fast was the loading and display of AR content (VPS, SLAM) indoors?"
- "How fast was the loading and display of AR content (VPS, SLAM) outdoors?"

Responses were given on a 5-point Likert scale (1 = Very slow, 5 = Very fast). As shown in Table VII, users rated the application slightly higher in terms of speed indoors (M = 3.81, SD = 0.83) than outdoors (M = 3.71, SD = 0.88).

TABLE VII. DESCRIPTIVE STATISTICS FOR PERCEIVED AR LOADING SPEED INDOOR VS. OUTDOOR

Variable	Mean	Std. Deviation	N
Indoor AR Loading Speed	3.81	0.83	256
Outdoor AR Loading Speed	3.71	0.88	256

A paired-samples t-test revealed a statistically significant difference between the two contexts, t(255) = 2.167, p = 0.031 (see Table VIII). The mean difference of +0.10 confirms that the application was perceived as faster indoors.

TABLE VIII. PAIRED-SAMPLES T-TEST FOR AR LOADING SPEED IN INDOOR VS. OUTDOOR CONTEXTS

Variable Pair	Mean Difference	t	df	Sig. (2-tailed)
Indoor vs. Outdoor AR Loading Speed	+0.102	2.167	255	0.031

These results support the hypothesis that AR content was perceived to load more quickly in indoor environments. Several factors may account for this, including:

- more consistent lighting conditions and surfaces,
- better tracking support from structured geometry (walls, doors),
- more reliable indoor connectivity (Wi-Fi vs. mobile data).

From a usability standpoint, this finding highlights the need for optimizing AR systems for outdoor performance – possibly through enhanced tracking algorithms or adaptive rendering for varying environmental conditions. Fig. 5 illustrates the distribution of perceived utility scores of the application based on the type of device used.

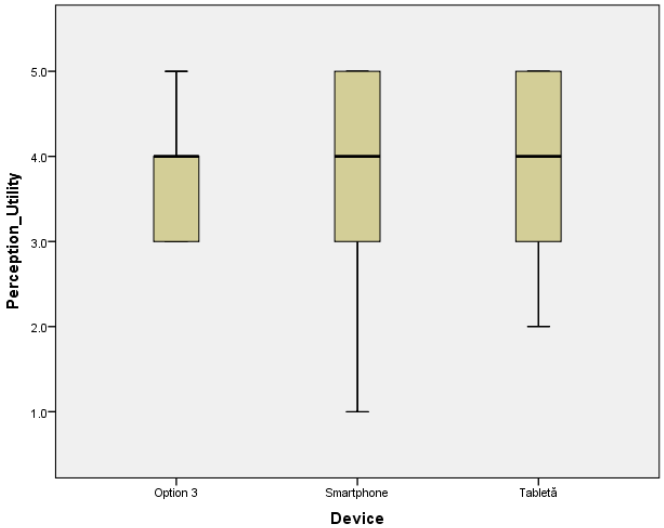


Fig. 5. Distribution of perceived utility scores by device type. Median utility is higher for smartphones and tablets compared to laptops (Option 3). The wider range for smartphones suggests a more varied but generally positive user experience.

A higher median is observed for smartphones and tablets compared to “Option 3” (likely representing laptops). Smartphone users reported a wider range of perceptions (with values ranging from 1 to 5), suggesting a more variable experience, but with an overall positive tendency. This distribution supports Hypothesis H4, which states that the application is perceived as more useful when used on a smartphone.

E. Hypothesis 5 (H5): Users are more Likely to Express an Intention to Regularly use the Application for Indoor Navigation than for Outdoor Navigation

The fifth hypothesis explored whether students reported a higher behavioral intention to regularly use the AR navigation application in indoor settings (e.g., classrooms, hallways) compared to outdoor navigation (e.g., between buildings across the campus). Behavioral intention is a central variable in the Technology Acceptance Model (TAM) and Unified Theory of Acceptance and Use of Technology (UTAUT), as it directly influences actual technology adoption.

To examine this hypothesis, participants responded to the following parallel statements:

- “I would be willing to regularly use this application for indoor navigation on campus.”
- “I would be willing to regularly use this application for outdoor navigation between campus buildings.”

Responses were measured using a 5-point Likert scale (1 = Strongly disagree, 5 = Strongly agree). Descriptive statistics presented in Table IX revealed virtually identical mean scores: indoor (M = 3.93, SD = 1.03) and outdoor (M = 3.93, SD = 1.00), suggesting no practical difference in user intention across environments.

TABLE IX. DESCRIPTIVE STATISTICS FOR INTENTION TO USE INDOOR VS. OUTDOOR

Variable	Mean	Std. Deviation	N
Intention to Use (Indoor)	3.93	1.03	256
Intention to Use (Outdoor)	3.93	1.00	256

The paired-samples t-test confirmed this equivalence, showing no statistically significant difference between the two scores:

$t(255) = 0.079$, $p = 0.937$ (see Table X). The mean difference was negligible (+0.004), indicating consistent behavioral intention across indoor and outdoor contexts.

TABLE X. PAIRED-SAMPLES T-TEST FOR INTENTION TO USE

Variable Pair	Mean Difference	t	df	Sig. (2-tailed)
Indoor vs Outdoor intention to use	+0.004	0.079	255	0.937

These findings suggest that users are equally inclined to use the application regularly in both indoor and outdoor navigation contexts. This result reinforces the idea that user trust in the application extends across different spatial environments, likely due to a coherent interface and consistent interaction model.

This outcome is encouraging from a scalability perspective, indicating that future AR implementations in university campuses may find equal acceptance for both indoor and outdoor orientation support.

F. Hypothesis 6 (H6): Users Perceive the Application's Localization Accuracy and Stability as Significantly Higher in Indoor Scenarios than in Outdoor Scenarios

The sixth hypothesis addressed the perception of localization quality – a crucial factor in the effectiveness of augmented reality (AR) navigation tools. AR experiences depend heavily on stable and precise positioning, typically achieved through technologies such as VPS (Visual Positioning System) and SLAM (Simultaneous Localization and Mapping). Given the more controlled conditions in indoor environments (e.g., structured geometry, constant lighting, Wi-Fi signals), it was expected that localization would be perceived as more stable indoors than outdoors.

To assess this, participants evaluated two items:

- “How would you rate the stability and accuracy of the localization function in indoor navigation (buildings, hallways)?”
- “How would you rate the stability and accuracy of the localization function in outdoor navigation?”

Each was measured on a 5-point Likert scale (1 = Very low, 5 = Very high). Descriptive statistics are shown in Table XI, revealing a slightly higher mean for indoor localization (M = 3.68, SD = 0.86) than for outdoor (M = 3.63, SD = 0.88).

TABLE XI. DESCRIPTIVE STATISTICS FOR PERCEIVED LOCALIZATION ACCURACY IN INDOOR VS. OUTDOOR CONTEXTS

Variable	Mean	Std. Deviation	N
Indoor Localization Accuracy	3.68	0.86	256
Outdoor Localization Accuracy	3.63	0.88	256

The paired-samples t-test indicated that the difference in perceived accuracy was not statistically significant, $t(255) = 1.080$, $p = 0.281$ (see Table XII). The mean difference was only +0.051.

TABLE XII. PAIRED-SAMPLES T-TEST FOR LOCALIZATION ACCURACY SCORES

Variable Pair	Mean Difference	t	df
Indoor vs Outdoor Localization Accuracy	+0.051	1.080	255

Although the hypothesis was not supported statistically, the result suggests that users generally perceive localization to be similarly stable in both environments, with a slight (non-significant) preference for indoor performance. This outcome may be attributed to improvements in mobile AR tracking technologies and robustness across spatial contexts.

Designers and developers should nonetheless consider environmental differences when optimizing positioning systems, particularly for outdoor use cases involving variable light, weak signals, or open unstructured areas.

V. DISCUSSION AND LIMITATIONS

The results of this study provide empirical evidence that a unified, infrastructure-free AR navigation system can deliver a consistent and usable experience across both indoor and outdoor university environments. Participants reported similar levels of intuitiveness, usefulness, engagement, and behavioral intention to reuse the application regardless of spatial context, as measured through the System Usability Scale (SUS) and the Technology Acceptance Model (TAM). The only statistically significant difference was a slight advantage in perceived AR content loading speed in indoor scenarios, likely due to more stable lighting and connectivity conditions.

These findings reinforce the initial design assumption that a consistent user interface and interaction model can minimize the cognitive gap between indoor and outdoor usage. The results also address the core research question posed in this study: Can a single AR navigation system maintain usability and user acceptance across spatial contexts without reliance on GPS or external infrastructure? The answer, based on the data, appears to be affirmative.

From a comparative perspective, the usability scores obtained in this study (SUS ~74) align closely with values reported in prior AR navigation studies. For example, Chen et al. [17] reported a SUS score of 74 for an ARCore-based campus system, and Sato et al. [21] reported 76 in a museum setting. These similarities strengthen the external validity of our findings. Moreover, unlike BLE- or marker-based systems such as Yamamoto et al. [6], which required dense beacon deployment, our system operates solely on visual-inertial tracking and cloud-based spatial anchors—simplifying deployment and enhancing scalability.

Technical stability and system responsiveness have also been highlighted in previous literature as key predictors of user satisfaction [17], [23]. Our study extends these insights by showing that responsiveness perceptions remain stable even across variable lighting and open vs. closed environments. This outcome suggests that modern mobile AR frameworks like ARCore and ARKit can now support robust navigation without needing physical markers or dedicated sensors.

Despite the strengths of the approach, several limitations must be acknowledged. First, the experiment was conducted exclusively within a single university campus, which may limit the generalizability of the results to other institutional settings with different architectural layouts or technological infrastructures. Although both indoor and outdoor scenarios were evaluated, the tasks involved relatively short, predefined routes. Longer or more complex navigation scenarios—such as multistep journeys involving transitions between buildings—were not assessed and may yield different results in terms of user satisfaction and system responsiveness.

Second, all participants used their personal smartphones, which, while realistic and ecologically valid, introduced variation in hardware performance and environmental adaptation (e.g., screen brightness outdoors, camera quality). These variables were not controlled or measured and may have introduced noise into user experience ratings.

Lastly, although this study employed validated instruments (SUS and TAM) for assessing usability and acceptance, it relied solely on post-task self-reported measures. Objective performance metrics such as navigation time, error rate, path deviation, or eye-tracking data were not collected. Integrating such data in future research would complement subjective feedback and allow more comprehensive usability evaluation.

Overall, this study demonstrates that consistent AR navigation performance can be achieved across spatial contexts using a single, infrastructure-independent mobile application. These findings support the development of scalable, user-centered AR wayfinding systems suitable for real-world academic deployments.

VI. CONCLUSION

This study investigated whether a single mobile augmented reality (AR) navigation application could provide a consistent and usable experience across both indoor and outdoor university environments. Using a within-subjects experimental design with 256 participants, the system was evaluated through established usability and acceptance frameworks (SUS and TAM) and demonstrated strong performance in both spatial contexts.

The findings validate the feasibility of infrastructure-free, camera-based AR navigation solutions in academic settings. By maintaining consistent interaction patterns and localization methods across environments, the application enabled users to navigate seamlessly, regardless of whether they were indoors or outdoors. This cross-context adaptability addresses a key challenge in smart campus design, where traditional tools often fail to bridge spatial transitions.

Future work will extend this research along several directions. First, incorporating objective performance metrics such as route efficiency, task duration, and error rates would complement subjective assessments. Second, the system could be deployed and evaluated in campuses with more complex spatial configurations or across multiple institutions. Third, integration with real-time data (e.g., scheduling, crowd flow) and accessibility enhancements (e.g., voice-only guidance or screen-reader support) may further improve adoption and inclusivity.

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