International Journal of Sustainable Development and Planning
Vol. 21, No. 6, June, 2026, pp. 2467-2477
Journal homepage: http://iieta.org/journals/ijsdp

Towards a Sustainable Digital Planning Model for Traffic Management in Religious Heritage Cities: Employing Augmented Reality and Space Syntax in the Historical Center of Karbala

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https://doi.org/10.18280/ijsdp.210607

Received: 7 May 2026
Revised: 24 June 2026
Accepted: 29 June 2026
Available online: 30 June 2026

Keywords:
augmented reality, cognitive layer, wayfinding, crowd management, religious cities, seasonal religious visitation, Space Syntax

ABSTRACT

Religious heritage cities face increasing pressure during major pilgrimage seasons. The movement of large crowds can impair spatial clarity, reduce visitor awareness of movement, and hinder access to services, while also limiting the possibility of physical intervention in the historical fabric. This study presents an exploratory field assessment of the potential of a web-based augmented reality (AR)-enhanced digital navigation interface (NAI) as a lightweight, non-structural knowledge layer to enhance the visitor experience in the historical center of Karbala. The research employed a quasi-experimental pre/post design with a single group, integrating Space Syntax analysis using DepthmapX with a purposive field experiment involving a sample of 50 participants distributed across three spatial scenarios. The analysis revealed that Al-Jumhuriya and Al-Sidra Streets were the most integrated axes, with T1024 values of 535 and 517, respectively. These results formed the basis for developing the AR Karbala Navigator model using HTML5, JavaScript, Leaflet.js, and browser-based positioning and orientation techniques. The results showed statistically significant improvements in spatial perception, navigation efficiency, crowd awareness and rerouting, and access to services, with the greatest improvement in crowd awareness. Expert evaluation also supported the apparent validity and professional acceptability of the model. However, the results should be interpreted as preliminary indicators rather than conclusive evidence due to the absence of a control group and limitations in positioning accuracy.

1. INTRODUCTION

Heritage cities hold a unique place in urban studies. They carry centuries of history, culture, and collective memory within their physical fabric, while at the same time functioning as living urban spaces that must respond to the demands of modern life and seasonal mass gatherings. The historic urban fabric of these cities developed gradually over long periods, shaped by sacred proximity and functional accumulation, creating dense networks of narrow streets and overlapping uses that reflect a deep relationship between people and place [1, 2]. However, this same historic character makes them structurally fragile. The narrow streets and organic layouts that define their heritage value become serious obstacles when large numbers of visitors arrive in a short period, creating spatial confusion and placing enormous pressure on infrastructure and movement networks [3, 4].

This challenge is most visible in Islamic heritage cities, which regularly receive millions of visitors during major religious seasons that far exceed the original design capacity of their historic cores. The holy city of Karbala represents one of the clearest examples of this condition ranking among the densest human gatherings in the world [5, 6]. Its historic centre is organised around the sacred axis connecting the two holy shrines [6], with a pedestrian network of alleyways ranging between 6 and 16 metres in width. The city receives millions of visitors annually across successive religious seasons, and urban expansion data show that its built-up area grew by more than 24% between 2015 and 2022 [7], without a matching development in the spatial information systems needed to guide visitors and manage crowd movement along the main corridors leading to the two shrines. The result is a structural cognitive gap [2, 3]: visitors cannot build a clear mental map of their surroundings or respond effectively to crowd dynamics around them, not because they are unfamiliar with the place, but because the environment itself cannot maintain spatial legibility under field-observed crowd pressure.

Web-based augmented reality (AR) offers a practical response to this problem. By overlaying real-time spatial information directly onto the visitor's view through a mobile phone browser, AR can transform the historic urban fabric from a source of spatial confusion into a supportive cognitive resource that helps visitors find their way and allows crowd management authorities to distribute real-time guidance according to individual needs [8]. Despite the growing body of AR research in heritage contexts [9, 10], experimental evidence for its effectiveness as a cognitive support tool in Islamic heritage cities under real extreme-density conditions remains scarce. Existing studies [11-13] were conducted under normal density conditions or in controlled indoor settings, and none tested an AR system within the morphological complexity and crowd pressures characteristic of a religious pilgrimage environment [5]. This gap is the central motivation for the present study.

This study aims to provide an exploratory field assessment of the potential of a web-based AR-enabled digital navigation interface (NAI) in supporting spatial awareness and crowd awareness management within the historic center of Karbala during the pilgrimage season. The study achieves this through three interconnected objectives: first, identifying the most cognitively stressful pathways by analyzing spatial integration using Space Syntax methodology; second, developing a lightweight digital model that serves as a cognitive layer to aid spatial orientation and crowd awareness; and third, examining pre- and post-improvement indicators in participant responses within a quasi-experimental field trial.

The study's contribution lies in providing a preliminary field indicator of the applicability of digital cognitive layers in densely populated religious heritage cities, rather than offering definitive causal evidence of effectiveness. Furthermore, the study seeks to propose a scalable model that can enhance visitor safety and spatial awareness without disrupting the heritage fabric, aligning with the Sustainable Urban Development Goals, particularly Goal 11, which focuses on making cities more inclusive, safe, resilient, and sustainable.

Because the study relies on a quasi-experimental design for a single pre/post measurement group, its results are not presented as definitive causal evidence, but rather as preliminary indicators that support the need for more controlled subsequent tests, including a control group or comparison with conventional navigation instruments.

2. LITERATURE REVIEW

2.1 Augmented reality in heritage wayfinding and crowd management

A selective critical review of recent scholarship has advanced the understanding of AR in heritage and navigation contexts, yet a critical gap persists at the intersection of AR-based cognitivesupport, crowd management, and extreme-density pilgrimage settings. The four most pertinent and recent studies are reviewed below to delineate the precise contours of this gap (Table 1).

Table 1. Comparative review of the four most relevant recent studies

Study	Focus	Methodology	Density/Context	Primary Outcome and Remaining Gap
[11]	AR navigation effectiveness	Systematic review and meta-analysis	Varied, mostly normal-density settings	Reported positive effects of AR on wayfinding performance; however, no study was situated in a pilgrimage context or under high crowd pressure.
[12]	Gamified AR crowd management	Prototype development	Low-density indoor museum setting	Demonstrated conceptual feasibility of AR-supported visitor flow management, but did not address Islamic heritage cities or dense pilgrimage movement.
[13]	AR-supported mental map construction	Human-centred experimental study	Normal-density urban setting	Reported improvements in spatial cognition, but did not include crowd pressure as a field variable.
[14]	Crowd management during Hajj	Observational analysis	High-density Islamic pilgrimage context	Provided valuable insights into crowd dynamics, but did not test an AR-based digital intervention or measure cognitive outcomes.
Present study	Web-based AR-enhanced cognitive navigation layer	Exploratory single-group pre-test/post-test field assessment	Field-observed high crowd pressure in a religious heritage city	Provides preliminary indicators on spatial perception, navigation efficiency, crowd awareness, and service access; further controlled testing is required.

Source: Author.

Man et al. [11] conducted a comprehensive systematic review and meta-analysis of 13 studies involving 400 participants, confirming that AR significantly enhances wayfinding performance (SMD = 0.992) and overall navigation effectiveness (overall effect size =0.554). Despite the robustness of this meta-analytic evidence, the authors identified no study situated within a pilgrimage context or involving extreme pedestrian density, thereby empirically substantiating the research gap that the present study addresses.

In the domain of AR-enabled crowd management, Koulouris et al. [12] proposed a gamified AR prototype integrating computer vision for visitor flow regulation in a museum environment. Although this work demonstrates the conceptual feasibility of AR-based crowd management, it is confined to a controlled, low-density, indoor setting and does not engage with the morphological complexity or spiritual sensitivities characteristic of heritage religious cities.

Complementing these navigation and management perspectives, Zhang et al. [13] examined immersive AR-based navigation systems and reported improvements in cognitive map development and wayfinding performance; however, their study was conducted in an indoor environment and did not address crowd pressure in religious heritage settings.specifically aimed at supporting mental map construction and wayfinding. Their experimental findings confirmed significant improvements in spatial cognition [15]; however, the study was conducted under normal-density urban conditions and did not incorporate crowd pressure as an experimental variable, limiting its applicability to high-density pilgrimage environments.

Within the specific context of Islamic mass gatherings, Attia and Farhan [5] discussed urban heritage revitalization challenges in the holy city of Karbala, highlighting the need for strategies that balance heritage preservation with visitor-related urban pressures. While the study provides valuable insights into crowd dynamics and recommends improvements in urban design and simulation, it remains purely observational and does not test any digital AR intervention or measure cognitive outcomes.

None of the most advanced and directly relevant studies to date has deployed and experimentally tested an AR system as a dual-function cognitive layer for wayfinding and crowd management within an Islamic heritage pilgrimage environment under authentic extreme-density conditions. The present study is specifically designed to fill this multi-dimensional gap [5, 11-13].

2.2 Theoretical framework

The study is grounded in four complementary theories that collectively explain the cognitive collapse in high-density pilgrimage environments and underpin the design of the AR model as a dual-function cognitive layer. The term "cognitive layer" is used throughout this study in a precise operational sense: a real-time digital stratum superimposed onto the physical urban environment that neither replaces nor restructures the heritage fabric, but selectively filters, reconstructs, and redistributes spatial information to compensate for the perceptual failures induced by high crowd pressure. What distinguishes a cognitive layer from a conventional navigation application is its dual function—simultaneously supporting individual wayfinding decisions and enabling collective crowd-flow management-and its theoretical grounding in the gap between available and required cognitive resources as defined by Sweller [3].

1. Cognitive Load Theory [3]: The convergence of crowd navigation, visual noise, and information scarcity inflates extraneous cognitive load, depleting the visitor's mental energy and weakening both individual wayfinding and responsiveness to crowd management guidance. The model addresses this by offloading cognitive tasks to the device interface and filtering environmental information to the essential minimum [16].

2. The Image of the City [2]: The legibility of paths, nodes, landmarks, edges, and districts collapses under crowd pressure and temporary structures. The AR layer digitally reconstructs these elements: directional arrows clarify paths, service markers highlight nodes, and annotations preserve landmark reference points, supporting both individual orientation and collective flow management [15].

3. Situation Awareness Theory [17]: The visitor's awareness of their surroundings collapses sequentially (perception → comprehension → projection), reducing them to a particle adrift in the crowd. The model restores this awareness through real-time feedback: displaying occluded elements, facilitating comprehension of spatial relationships, and visualising live density ahead to enable risk projection [18].

4. Genius Loci/Spirit of Place [4]: Wayfinding in Karbala is not a geometric transfer but an integral part of the spiritual experience. The collision of "Transient Urbanism" with the permanent heritage fabric weakens the visitor's connection to the identity of the place. The digital intervention is anchored in the principle of "Augmentation, not Replacement" to restore the legibility of the latent heritage fabric and preserve the spirit of the place [9, 10].

5. Space Syntax theory [1] provides the analytical foundation for understanding the relationship between the topological structure of the street network and the natural movement patterns of pedestrians within it [19, 20]. Integration values derived from Space Syntax analysis are not merely descriptive metrics but predictive indicators of pedestrian flow, establishing a mathematically grounded criterion for identifying the corridors of maximum cognitive stress and embedding spatial evidence directly into the routing logic of the AR model. This theoretical grounding distinguishes the present intervention from conventional navigation applications by anchoring its design decisions in the morphological properties of the historic fabric itself rather than in arbitrary spatial assumptions.

The conceptual logic of the study follows a five-step causal chain, as illustrated in Figure 1 the morphological complexity of the historic urban fabric generates a structural cognitive gap in the visitor, which the AR intervention addresses through real-time spatial information, producing measurable behavioural and cognitive improvements.

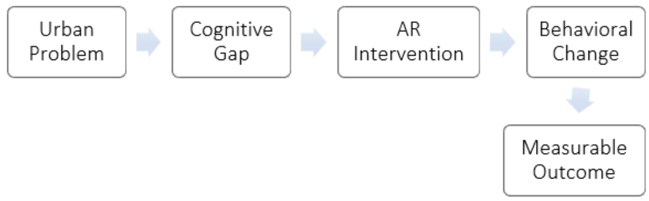


Figure 1. Causal framework of the study
Source: Author.

3. STUDY AREA

The holy city of Karbala is located approximately 110 kilometres south of Baghdad in central Iraq [6]. Its historic urban core is structured around the sacred axis linking the Holy Shrine of Imam Hussein to the east and the Holy Shrine of Al-Abbas to the west, featuring an organically evolved pedestrian network with alleyways ranging from 6 to 16 metres in width [6]. Spatial integration analysis (Space Syntax) revealed that the highest network integration values (T1024 = 535 and 517) are concentrated in Al-Jumhuriya and Al-Sidra streets, establishing them as the most heavily trafficked pedestrian corridors and the most intense loci of both crowd management and wayfinding challenges [5, 19].

The historic centre of Karbala constitutes a rare "natural laboratory" for testing the cognitive layer hypothesis: the very morphological properties that confer its heritage value-organic non-linearity, constrained visual axes, and truncated sightlines [1, 2] are precisely those that, under the multi-million-strong densities of the Arbaeen season [5, 6], produce an acute structural cognitive crisis wherein the visitor is rendered incapable of constructing a coherent mental map [2, 3] or responding effectively to the dynamics of the crowd [17]. This rare convergence of heritage urban fabric and exceptional human pressure justifies the selection of the site as an extreme test case for the validity of the proposed digital model for combined crowd management and wayfinding [21].

4. MATERIALS AND METHODS

This study adopted an exploratory field methodology with a quasi-experimental pre-/post-test design for a single group. Its aim was to examine preliminary indicators of the potential of a web-based AR-enhanced digital NAI in supporting spatial perception, enhancing crowd awareness, and improving access to services within the historic center of Karbala during the pilgrimage season. The methodology combined spatial analysis using Space Syntax methodology with the development of a pilot digital model, followed by field testing on a purposive sample of visitors. Given the single-group pre-/post-test design, the results are interpreted as preliminary indicators that can be further verified, and not as definitive causal evidence of the model's effectiveness. Figure 2 illustrates the overall methodological sequence of the study, from spatial diagnosis to model development, field application, statistical analysis, and expert evaluation.

Phase 1 Spatial *Diagnosis*	**Phase 2 Prototype *Development***	**Phase 3 Field *Implementation***	**Phase 4 Statistical *Analysis***	**Phase 5 Expert *Validation***
• **Space Syntax / DepthmapX** • **OpenStreetMap / QGIS** • **Al-Jumhuriya T=535** • **Al-Sidra T=517**	• HTML5 / Leaflet.js • Modified Dijkstra routing • Four display modes • ar2-2d0f2.web.app	• n=50 / Pre–Post test • Three field scenarios • 14-item questionnaire • $\Delta = Q3 - Q2$	• Wilcoxon / Paired t-test • $p < 0.001$ all axes • $r = 0.814$–0.856 • Highest $\Delta = +2.160$	• n=60 academics • 5 axes / 21 items • Overall mean 3.729/5 • Results confirmed

Figure 2. Methodological flowchart of the study
Source: Author.

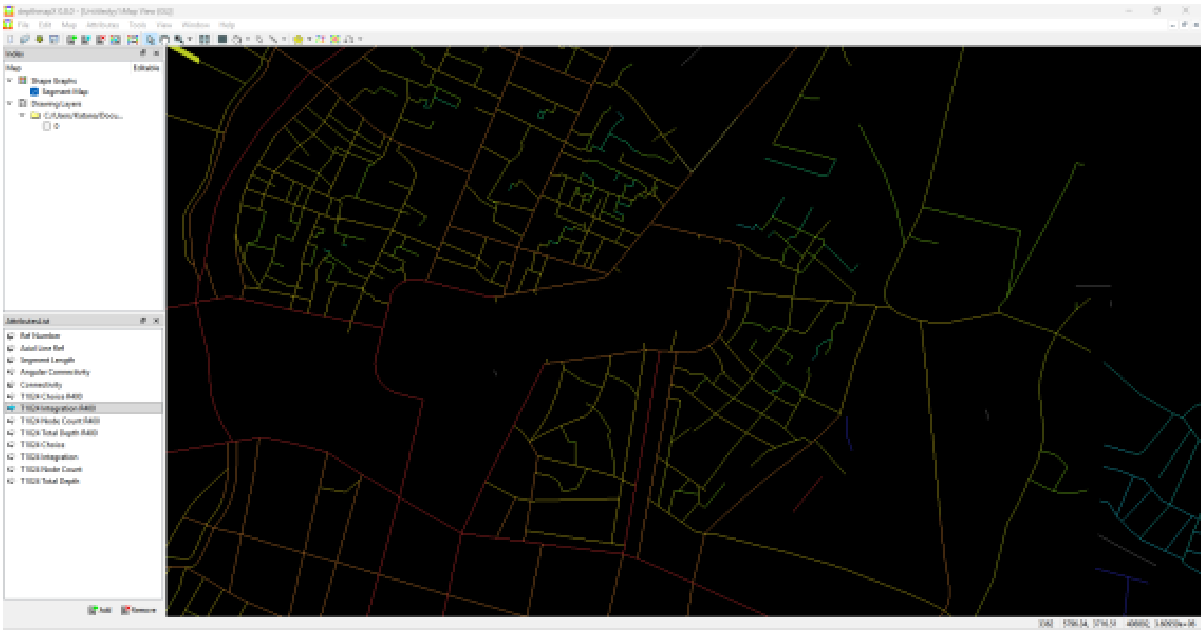


Figure 3. Spatial integration map of the historical center of Holy Karbala extracted from DepthmapX 0.8
Source: Author.

Figure 4. Field documentation of the two study corridors during the religious visitation season
Source: Author field documentation.

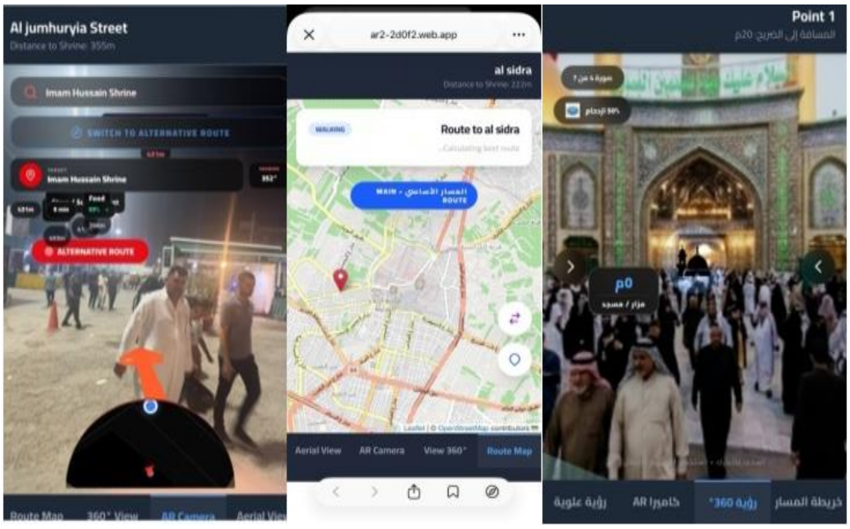


Figure 5. Interface screenshots of the augmented reality (AR) Karbala
Source: Author.

The methodology began with the spatial diagnosis phase, where the street network was extracted from digital map sources, processed within a Geographic Information System (GIS) environment, and then entered into DepthmapX software for spatial integration analysis. Integration values, particularly the T1024 index, were used to identify the most clearly defined and integrated axes within the morphological structure of the historic center. The analysis showed that Al-Jumhuriya and Al-Sidra Streets were among the most integrated axes within the network, with T1024 values of 535 and 517, respectively. Figure 3 shows the spatial integration map of Karbala's historic center as derived from the Space Syntax analysis. These results were used to determine the locations of field scenarios and to establish the initial spatial foundation for the digital model (Figure 4). It is important to note that integration values are understood in this study as indicators of spatial clarity and readability, not as direct indicators of reduced or avoided congestion.

The model used in this study was developed as a web-based AR-enabled digital NAI, not a full-fledged AR system based on live visual overlays or precise spatial fixation. The model was built using HTML5, CSS3, JavaScript, and the Leaflet.js library to function as a progressive web application accessible via a mobile browser without requiring a separate app installation. It utilizes the Web Geolocation API to determine the user's approximate location and DeviceOrientationEvent to estimate device orientation. The model then displays spatial cues and orientation information to help the visitor understand their location, orientation, and relationship to surrounding corridors and services. In this study, the term "AR" refers to the addition of a lightweight spatial information layer via the browser, rather than a full-fledged AR system based on SLAM, VPS, visual markers, or fixed spatial anchors. Figure 5 shows screenshots of the AR Karbala Navigator model interface as used in the field experiment.

The routing logic in the current version of the model relies on spatial clarity derived from Space Syntax analysis, rather than a fully dynamic rerouting based on real-time crowd data. Spatial integrity values were used as an indicator of corridor readability and were then integrated into a modified routing algorithm based on Dijkstra logic. Therefore, the current model selects the most morphologically distinct routes, not necessarily the least congested. The study acknowledges that relying solely on spatial integration is insufficient for crowd management in high-traffic environments, as the most integrated axes may also be the most pedestrian-friendly and congested. Accordingly, the current routing logic is understood as a preliminary step toward aligning the model with the city's spatial structure. Future iterations will be based on a composite cost function that combines route length, observed or estimated crowd density, temporary obstruction risk, route clarity, and proximity to urban services.

Regarding positioning, mobile and web browser location data were treated as approximate data at the urban corridor level, rather than precise data at the meter or sidewalk level. This is due to the nature of Karbala's historical fabric, which includes narrow streets and alleyways where positioning signals may be affected by reflections, multiple paths, and the inherent inaccuracy of dense urban environments. Therefore, the model was not used in this study as a critical safety tool or a precise emergency routing system, but rather as an aid layer for general spatial awareness, providing approximate guidance on directions, routes, and service locations. A low-pass filter was also used to reduce fluctuations in device orientation data and improve the stability of signals displayed to the user. Table 2 shows the data sources used in the study, including the street network, spatial integrity values, approximate positioning data, device orientation data, field observation records, pre- and post-tests, and a user acceptance questionnaire.

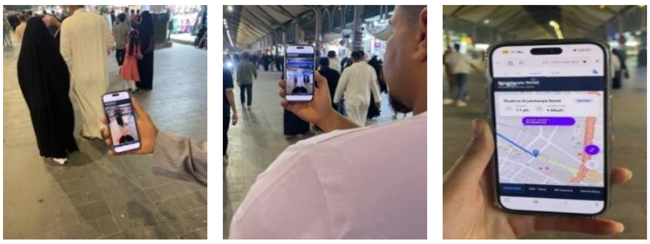
The study employed a purposive sample of 50 participants, selected from visitor categories most likely to experience spatial awareness issues during their visit, particularly first-time visitors, repeat visitors with varying degrees of spatial familiarity, and visitors experiencing high crowd pressure. Since the study did not employ a random probability sampling method, the adequacy of the sample was not justified by random selection equations, but rather by the nature of the quasi-experimental exploratory design based on pre-/post measurement, and by the suitability of the purposive sample for the objectives of the field experiment. In this design, each participant acts as a self-comparison before and after using the model, which helps to minimize the effect of individual differences among participants. Therefore, the sample here is understood as suitable for testing the indicators of suitability and usability in a preliminary field study, not for the purpose of broad statistical generalization to all visitors to Karbala.

Table 2. Inventories the complete dataset

Data Type	Primary Source	Format	Purpose
Street network data	OpenStreetMap (OSM)/QGIS export	DXF/Shapefile	Construction of the segment map in DepthmapX 0.8 for Space Syntax integration analysis.
Spatial integration values (T1024)	DepthmapX 0.8 computation from OSM-derived segment map	Numerical/GeoJSON	Identification of morphologically readable corridors and input for the modified routing logic.
GPS/geolocation data	Web Geolocation API	Approximate real-time coordinates	Corridor-level positioning for general orientation and route support; not used for precise metric navigation.
Device orientation data	DeviceOrientationEvent API with low-pass filtering	Heading degrees (°)	Estimation of device direction and stabilization of orientation cues displayed to the user.
Field observation records	Direct field observation during the pilgrimage season	Qualitative field notes and visual documentation	Contextual validation of scenario design and documentation of observed crowd pressure conditions.
Pre-test questionnaire	14-item Likert-scale questionnaire administered before prototype use	Ordinal data, 50 × 14 items	Establishing the baseline spatial-cognitive profile across the four measurement axes.
Post-test questionnaire	14-item Likert-scale questionnaire administered immediately after prototype use	Ordinal data, 50 × 14 items	Measuring post-use spatial-cognitive responses and calculating pre/post differences.
User acceptance survey	Post-test 7-item evaluation instrument	Ordinal data, 50 × 7 items	Assessing perceived usability, information clarity, spiritual/spatial experience, and recommendation intent.
Expert survey	Questionnaire administered to 60 academic specialists	Ordinal data	Assessing face validity, content relevance, professional acceptability, and future scalability.

The field experiment was further supported by an independent survey of 60 academic experts in architecture, urban design, AR technologies, heritage preservation, and crowd management. This survey was used to support the apparent validity, content suitability, professional acceptability, and future scalability of the model, not to prove its effectiveness in actual user performance. Therefore, the expert evaluation complements the field experiment and is not a substitute for a controlled pilot test involving a control group or a comparison with traditional navigation tools.

The field experiment was structured around three spatial scenarios derived from actual movement patterns within the historic center of Karbala during the pilgrimage season. The first scenario represented a visitor struggling to form a clear mental map within a relatively crowded area. The second scenario represented a repeat visitor with prior knowledge of the location but experiencing greater crowd pressure and requiring support in spatial decision-making. The third scenario represented confusion or hesitation at visually similar intersections and passageways. These scenarios were designed to test four key dimensions: spatial perception and mind mapping, navigational efficiency, crowd awareness and rerouting, and access to urban services. Table 3 details the field scenarios in terms of location, participant type, observed crowd pressure, main perceptual challenge, and the tested model function. Figure 6 illustrates a field application of the model on Republic Street during peak visiting season.



(a) (b) (c)

Figure 6. Field implementation of the augmented reality (AR) Karbala prototype during the religious visitation season on Al-Jumhuriya Street, showing participants using the application under real crowd conditions
Source: Author.

Table 3. Field scenario specifications for the exploratory pre-test/post-test assessment

Scenario	Location	Participant Profile	Field-Observed Crowd Condition	Main Spatial-Cognitive Challenge	Prototype Function Tested
S1	Al-Jumhuriya Street	First-time or low-familiarity visitor	Moderate to high pilgrimage crowd pressure	Difficulty forming an initial mental map due to visual complexity, temporary structures, banners, and limited landmark visibility.	Basic spatial orientation, landmark recognition, and route comprehension.
S2	Al-Jumhuriya Street	Repeat visitor with prior spatial familiarity	High field-observed crowd pressure	Decision hesitation under crowd pressure, reduced route clarity, and reliance on informal guidance from others.	Navigation efficiency, route guidance, and reduced perceived reliance on asking others.
S3	Al-Sidra Street intersection	Visitor experiencing directional confusion at an intersection	High crowd pressure with visual ambiguity at corridor junctions	Loss of direction, uncertainty between visually similar corridors, and difficulty in reorientation after spatial confusion.	Crowd-awareness support, reorientation cues, and access to nearby services.

Source: Prepared by the authors based on field observation and the exploratory implementation of the AR Karbala Navigator prototype.
Note: Crowd conditions were described based on field observation during the pilgrimage season. Since no direct persons-per-square-metre measurement was conducted, the terms used in this table refer to observed crowd pressure rather than quantified crowd density.

Data were collected using a 14-item Likert scale questionnaire administered to participants in two phases: before and immediately after using the model. This allowed for measuring the change in participants' responses between the pre- and post-tests for each dimension of the study. User acceptance data was also collected through a post-test questionnaire focusing on ease of use, clarity of information, speed of response, support for mind mapping, the model's impact on the spiritual and spatial experience, and the willingness to recommend it. These results should not be interpreted as definitive causal evidence due to the absence of a control group, but rather as preliminary indicators of the model's ability to support spatial perception and crowd awareness in a crowded field setting.

The statistical analysis began by examining the nature of the data distribution using the Shapiro-Wilk test to determine the appropriate test for each study axis. Based on the distribution analysis results, the Wilcoxon signed-rank test for paired samples was used for axes where the normality assumption was not met, with the effect size calculated using $r = Z/\sqrt{N}$. For axes that met the normality criteria, the paired samples t-test was analyzed, and the effect size was calculated using Cohen's d. The study adopted a significance level of 0.05, with results considered highly significant at $p < 0.001$. The statistical procedures used were also explained, including the type of test, the nature of the data, the significance level, the method for calculating the effect size, and the approach to handling incomplete data. No missing data were present in the final dataset.

To enhance the reliability of the research procedure, a methodological triangle was adopted, linking the outputs of spatial analysis, field experience data, participant responses, and expert evaluation. However, the study clearly adheres to its methodological limitations; it does not claim to provide definitive causal proof of the model's effectiveness, nor does it claim complete operational accuracy for the positioning system, nor does it present a complete model for dynamic crowd rerouting. Rather, it presents an exploratory field model of a lightweight digital knowledge layer that can support spatial clarity and the visitor experience in religious heritage cities, with the need for further development that includes a control group, more accurate crowd density measurement, integration of real-time crowd data, and more precise positioning techniques.

5. RESULTS

5.1 Results of spatial analysis

A spatial syntax analysis of the street network in the historic center of Karbala, using DepthmapX 0.8 software, revealed a clear gradient in spatial integration values among the traffic axes. Al-Jumhuriya Street recorded the highest integration value within the network at T1024 = 535, followed by Al-Sidra Street at T1024 = 517. These values are higher than those of the adjacent axes, which ranged approximately between 200 and 400. These results indicate that these two axes possess a high degree of morphological clarity and traffic attraction within the network, justifying their selection as suitable field contexts for model testing. However, these values do not necessarily imply that these axes are the least congested; rather, they may be the most attractive to traffic. Therefore, they should be understood as an indicator of spatial clarity, not a direct indicator of congestion avoidance.

5.2 Participants' prior cognitive profile

Pre-test results showed a general decrease in the mean scores across all four axes before the model was used, with values ranging from 2.000 to 2.260 on a five-point Likert scale. This pattern suggests that participants experienced significant cognitive difficulties in spatial awareness, orientation, crowd perception, and accessing services before using the digital NAI. This finding is particularly significant because a large proportion of participants had prior experience visiting the historic center, meaning that the poor pre-test performance cannot be explained solely by individual unfamiliarity but is also related to crowd pressure and the complexity of the urban fabric during the visit.

However, this result should be presented as a preliminary field indicator, not conclusive evidence, due to the absence of a parallel control group in the experimental design.

5.3 Descriptive comparisons between pre- and post-tests

Descriptive comparisons between the pre- and post-tests showed a clear improvement across all measurement axes after using the AR Karbala Navigator model. The mean spatial perception and mind mapping axis increased from 2.233 to 4.093, and the mean navigation efficiency axis increased from 2.260 to 4.028. The crowd awareness and rerouting axis showed the greatest improvement, rising from 2.000 to 4.160. The access to services and spatial experience axis also increased from 2.220 to 4.075. These results reflect a shift from a lower level of perception before using the model to a higher level after its use. However, this improvement should be interpreted as an improvement related to the pre-/post-test within the same group, and not as definitive causal evidence of the model's effectiveness (Table 4).

5.4 Statistical tests and effect sizes

The distribution of the data was examined using the Shapiro-Wilk test to determine the appropriate statistical test for each measurement axis. Based on the distribution analysis results, the Wilcoxon signed-rank test was used for axes that did not meet the normality assumption, while the Paired Samples t-test was used for axes that met the criteria for parametric analysis. All axes showed statistically significant differences between the pre- and post-tests at the $p < 0.001$ level, with very large effect sizes in all cases (Table 5).

The Wilcoxon signed-rank test results showed a significant improvement in the spatial perception and mind map formation axis, with a pre- and post-test difference of +1.860, a Z-value of 5.756, a $p < 0.001$, and a very large effect size ($r = 0.814$). The Crowd Awareness and Rerouting axis showed the greatest improvement among the axes, with a difference of +2.160, a Z-value of 6.053, a p-value < 0.001, and a very large effect size ($r = 0.856$).

For the axes that met the criteria for parametric analysis, the Paired Samples t-test showed a significant difference in the Navigation Efficiency axis, with the mean increasing from 2.260 to 4.028, a difference of +1.768, a $t(49)$ value of 10.225, a p-value < 0.001, a 95% confidence interval [1.421, 2.115], and a very large effect size ($d = 1.446$). The access to services and spatial experience axis also showed a significant difference between the pre- and post-tests, with the mean increasing from 2.220 to 4.075, a difference of +1.855. The t (49) value was 11.455, the p-value was < 0.001, and the 95% confidence interval was [1.530, 2.180], resulting in a very large effect size (d = 1.620).

These results indicate a clear pre-/post-test improvement in participants' responses after using the model. However, these results alone do not establish a definitive causal relationship, given that the study relied on a quasi-experimental design with one group and no parallel control group. Therefore, they should be interpreted as preliminary statistical indicators supporting the model's plausibility, not as conclusive evidence of its ultimate efficacy.

Table 4. The descriptive pre-test and post-test comparisons across the four measurement axes

Axis	Pre-Test Mean	Post-Test Mean	Improvement	Interpretation
Spatial perception and mental map formation	2.233	4.093	+1.860	Clear improvement in reading the urban setting and forming a mental image.
Navigation efficiency	2.260	4.028	+1.768	Improved route comprehension and reduced reliance on direct verbal guidance.
Crowd awareness and reorientation	2.000	4.160	+2.160	Highest improvement, suggesting the model's potential role in supporting spatial awareness under crowd pressure.
Access to services and spatial experience	2.220	4.075	+1.855	Improved perception of service locations and understanding of temporary spatial functions.

Source: Author by the researcher based on field data collection.

Table 5. Statistical test results and effect sizes across the four measurement axes

Axis	Test Used	Pre-Test Mean	Post-Test Mean	Difference	Z/t Value	p-Value	95% CI for Difference	Effect Size	Interpretation
Spatial perception and mental map formation	Wilcoxon Signed-Rank	2.233	4.093	+1.860	Z = 5.756	< 0.001	[1.227, 2.493]	r = 0.814	Very large
Navigation efficiency	Paired Samples t-test	2.260	4.028	+1.768	t(49) = 10.225	< 0.001	[1.421, 2.115]	d = 1.446	Very large
Crowd awareness and reorientation	Wilcoxon Signed-Rank	2.000	4.160	+2.160	Z = 6.053	< 0.001	[1.461, 2.859]	r = 0.856	Very large
Access to services and spatial experience	Paired Samples t-test	2.220	4.075	+1.855	t(49) = 11.455	< 0.001	[1.530, 2.180]	d = 1.620	Very large

5.5 User acceptance results

User acceptance assessments showed a generally positive level of appreciation for the AR Karbala Navigator model, with an overall average score of 4.164 out of 5, indicating a high level of acceptance. The item regarding the willingness to recommend the model scored the highest average at 4.75 out of 5, reflecting participants' perception of the model's usefulness and ease of use during the field experience. Items related to information clarity, support for mind mapping, ease of completing the visit, and lack of negative impact on the spiritual and spatial experience also received high averages, suggesting that participants viewed the model as a helpful tool for understanding the environment and navigating within a crowded context.

However, these results should be interpreted as an indicator of user acceptance and perceived usability, not as independent evidence of the model's operational effectiveness or causality. The high level of acceptance may be influenced by factors such as the novelty of the experience, participant expectations, and field application conditions. Therefore, while user acceptance results support the model's usability and potential for development, they are not sufficient on their own to establish its ultimate effectiveness without a control group or direct comparison with a traditional navigation tool.

5.6 Expert survey results

An expert survey of 60 academic specialists in urban design, architecture, AR technologies, heritage preservation, and crowd management was analyzed. The survey items were distributed across five main axes: spatial flow efficiency and movement clarity, mind map clarity and orientation efficiency, crowd safety and emergency response, preservation of spatial identity and heritage values, and AR as a tool for urban intervention.

The results showed a positive level of professional acceptance of the model, with an overall expert rating of 3.729 out of 5. The spatial flow efficiency and movement clarity axis ranked first with an average of 3.921, indicating that experts saw the model as potentially helpful in improving movement interpretation within the historical fabric. The crowd safety and emergency response axis ranked second with an average of 3.906, reflecting the experts' awareness of the importance of providing helpful information layers in crowded environments. The clarity of the mind map and navigation efficiency axis came next with an average score of 3.800, followed by the preservation of spatial identity and heritage values axis with an average score of 3.789. AR as a tool for urban intervention recorded the lowest average score of 3.325, indicating professional reservations related to aspects of the application, such as location accuracy, connectivity stability, and integration with existing crowd management systems.

However, the expert survey was not used to demonstrate the model's effectiveness at the level of actual user performance, but rather to assess apparent validity, content suitability, professional acceptance, and future scalability. Thus, the expert evaluation serves as a supportive and complementary level to field experience, and is not a substitute for a controlled pilot test with a control group or a comparison with traditional navigation tools. This framing helps keep the expert results within their proper methodological boundaries, as an indicator of professional acceptance and scalability, not a direct indicator of the model's operational effectiveness.

In general, the pre-/post-test results indicate a clear improvement in participants' responses after using the model, and user and expert acceptance scores suggest a positive reception to the idea and its potential applications. However, these results should be interpreted with caution; a quasi-experimental design with a single group does not allow for definitive proof of causation, and the absence of a control group leaves open the possibility of other factors influencing the outcome, such as increased familiarity with the task, novelty of the experience, or the expectation effect. Therefore, these results offer preliminary indications of the model's viability, but not conclusive evidence of its ultimate effectiveness.

6. DISCUSSION

The results of this study provide preliminary field evidence regarding the usability of a web-based AR-enhanced digital NAI in supporting spatial perception and crowd awareness within the historic center of Karbala during the pilgrimage season. Pre- and post-test results showed a clear improvement in participants' responses after using the model, particularly in the area of crowd awareness and rerouting, which recorded the highest improvement among the study's axes. However, these results should be interpreted with caution, as the design is a quasi-experimental, single-group design and does not include a parallel control group or direct comparison with a traditional navigation tool. Therefore, the results do not establish a definitive causal relationship between model use and cognitive improvement, but rather suggest a potential effect that warrants further investigation in more controlled studies.

From a cognitive load theory perspective, the improvement in participants' responses can be interpreted as a possible consequence of the model's role in reducing the external cognitive load on visitors. In crowded urban religious environments, crowd movement, temporary elements, signage, processions, and services all contribute to making spatial awareness and the formation of a clear mental map more challenging. In this context, the digital layer can play a supporting role by simplifying and presenting spatial information directly, such as traffic directions, service locations, and suggested routes. However, this interpretation remains theoretical and supported by preliminary field indicators. It cannot be considered definitive empirical confirmation without controlled testing that isolates the model's effect from other factors, such as the novelty of the experience, participant expectations, or increased familiarity with the task after the pre-test.

City image theory and situational awareness theory also help explain why the crowd awareness and rerouting axis recorded the highest improvement. In congested conditions, visitors not only struggle to find their way but may also have difficulty understanding their surroundings and anticipating potential blockages or hazards. Therefore, providing simplified spatial indicators via smartphone can help support situational awareness, especially at intersections, similar passageways, or locations where directions are difficult to discern. However, this result should be understood as a perceived and measured improvement based on participant responses, not as conclusive operational evidence of the model's ability to manage crowds in real time.

The results also suggest that subtle digital interventions may be more suitable for religious heritage cities than direct construction interventions. In the case of Karbala, the historical fabric is part of the symbolic and spiritual value of the place, and any extensive physical intervention, such as widening streets or removing architectural elements, could affect this value. Therefore, the concept of a "digital cognitive layer" offers a more sensitive planning approach, as it seeks to enhance the reading of the place without altering its physical structure. User evaluations showed that the model was not perceived as a distraction from the spiritual experience, but rather as an aid. However, user acceptance alone is insufficient to prove effectiveness, as it measures perception and usability more than actual operational performance.

The results of the expert survey should be understood within their proper methodological context. The results demonstrated good professional acceptance of the model concept and supported its apparent validity, content relevance, and scalability. However, expert evaluation does not replace controlled field testing, nor does it provide direct evidence of the model's effectiveness with users. Therefore, the expert survey should be treated as a supporting and complementary level of evaluation, not as independent proof of the model's success. In this sense, the expert survey supports professional acceptance, apparent validity, and content relevance, but it does not compensate for the lack of empirical verification with users under controlled comparative conditions.

The study also reveals important technical limitations that must be considered. The model used is a web-based AR-enhanced digital NAI, not a full-fledged AR system based on precise spatial fixation, SLAM or VPS-based visual overlays, or fixed spatial anchors. Furthermore, reliance on browser-based positioning results in approximate positioning accuracy, especially in dense urban environments where positioning signals may be affected. Since positioning errors can be significant compared to the width of historical corridors, the study's findings should be understood in terms of supporting general perception and broad trends, not precise metric navigation or critical emergency management.

From a planning perspective, the current routing model should not be interpreted as a complete system for dynamic rerouting and crowd management. The current version relies on spatial integration values derived from Space Syntax analysis to favor the most morphologically distinct axes. While this is a useful step for enhancing spatial readability, it is insufficient on its own to avoid congestion. The most integrated axes may simultaneously be the most attractive to pedestrians and the most congested. Therefore, future versions should aim to develop a composite routing function that combines route length, observed or estimated crowd density, temporary obstructions, proximity of services, and route morphological clarity. This would achieve a better balance between improving spatial readability and mitigating crowd pressure, rather than relying solely on the T1024 value.

Accordingly, the significance of this study lies not in proving the ultimate effectiveness of an intelligent navigation system, but rather in presenting a scalable exploratory model that integrates morphological analysis of the urban fabric, subtle digital intervention, and user experience in a crowded religious and heritage environment. The results provide a preliminary basis for designing more rigorous subsequent studies, which could include a control group, comparisons with traditional maps or signage, direct measurement of crowd density, and testing of more precise positioning techniques. In this sense, the study offers a preliminary methodological and applied contribution, not a definitive judgment on the model's effectiveness in all visit conditions.

7. CONCLUSIONS

The study concluded that using AR-enhanced web-based NAIs may represent a promising approach to enhancing spatial perception and crowd awareness in religious heritage cities with high visitor traffic. Pre- and post-test results showed significant improvements in spatial perception, navigation efficiency, crowd awareness and rerouting, and access to services. However, these results should be interpreted as preliminary indicators rather than definitive causal evidence, given the study's quasi-experimental design with a single group and the absence of a parallel control group.

The findings indicate that navigational difficulties within the historical center of Karbala are not solely related to visitor unfamiliarity but are also influenced by the complexity of the urban fabric, crowd pressure, and the interplay of temporary elements during the pilgrimage season. Thus, the problem extends beyond navigational aspects to encompass spatial and cognitive dimensions related to the visitor's ability to interpret the urban environment and form a clear mental map.

Furthermore, within the limitations of the current experiment, the results demonstrated that the model helped improve participants' responses after its use, particularly in the areas of crowd awareness and rerouting. This suggests that lightweight digital layers may be useful in environments where relying solely on traditional visual cues is difficult. However, this conclusion requires further, more rigorous testing, including direct comparisons with traditional navigation tools or a control group.

The study confirms that non-structural digital interventions can be suitable for religious heritage cities, as they aim to improve spatial readability without altering the urban fabric or compromising the site's spiritual and symbolic value. However, user and expert acceptance should be understood as an indicator of applicability and professional validation, not as independent proof of the model's ultimate effectiveness.

The study also highlights that the current version of the model has clear technical and methodological limitations. It relies on browser positioning, resulting in approximate location accuracy, and its current routing logic is based on morphological clarity derived from Space Syntax analysis. It does not yet integrate real-time data on crowd density or temporary obstructions. Therefore, the current model should be understood as a spatial awareness aid, not a comprehensive system for dynamic rerouting or critical safety management.

8. RECOMMENDATIONS AND FUTURE WORK

Based on the study's limitations and preliminary results, the study recommends conducting a more controlled follow-up experiment involving a control group or direct comparison with a conventional map or navigation tool to more accurately verify the model's impact.

It also recommends developing a quantitative protocol for measuring crowd density, including the number of people per square meter, observation time, and analysis of field images or videos, to allow for a more precise characterization of congestion.

Technically, a future version of the model should be developed using more accurate positioning technologies, such as VPS or spatial anchors, with a composite routing function that combines path length, crowd density, temporary obstructions, path clarity, and proximity of services.

Finally, the study recommends testing the model at similar religious and heritage sites to verify its scalability and applicability in other contexts.

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