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Optimization of a Wayfinding Visual Communication System for Intangible Cultural Heritage Exhibitions Based on Eye Tracking and Context-aware Sensing: A Case Study of Shanghai Jinshan Peasant Painting

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In this study, we developed a sensor-integrated evaluation framework for wayfinding visual communication in intangible cultural heritage exhibitions and validated it through a case study of the Shanghai Jinshan peasant painting exhibition. The objective of this study was to establish a quantitative and reproducible sensing-based framework for evaluating and optimizing wayfinding visual communication systems through the integration of eye tracking, context-aware sensing, task-performance analysis, and subjective evaluation. The proposed framework combined subjective ratings, task-performance indicators, eye-tracking metrics, and context-aware sensing variables to enable a comprehensive and quantitative assessment of visitor behavior, visual attention, and environmental influence. A two-stage experimental design was adopted. In Stage 1, an optimized wayfinding system was developed through design-principle review, expert consultation, and iterative pilot refinement. In Stage 2, a quasi-experiment was conducted with 60 participants, who were assigned to the original and optimized wayfinding groups (n = 30 each) and asked to complete five exhibition-guidance tasks. Multisource data collection included subjective scales, task completion time, task accuracy, time to first fixation, area-of-interest (AOI) attention ratio, and scan path concentration, as well as environmental sensing variables such as crowd density, illuminance, and viewing distance. The results showed that the optimized version significantly improved wayfinding clarity, exhibition understanding, and overall evaluation, with large effect sizes. It also significantly reduced completion time and improved task accuracy across all five tasks. At the eye-tracking level, the optimized version shortened the time to first fixation and increased the AOI attention ratio and scan path concentration, indicating more efficient visual guidance toward key information areas. Correlation analysis further revealed that better eye-tracking performance and task performance were associated with higher subjective evaluations. Regression analysis identified the

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wayfinding version as the most stable predictor of visual attention efficiency, task performance, and exhibition understanding/overall experience. These findings demonstrate that the proposed framework provides a measurable and reproducible approach for evaluating exhibition wayfinding systems and offers empirical evidence supporting the sensor-based optimization of visual communication in cultural exhibition environments.

1. Introduction

Intangible cultural heritage exhibitions should not be regarded as purely static presentations of cultural artifacts; rather, they constitute integrated human–environment interaction systems in which perception, cognition, recognition, and spatial movement occur within a measurable and dynamic sensing framework. From a sensors-oriented perspective, exhibition spaces can be conceptualized as data-rich environments where visitor behaviors are continuously influenced by visual stimuli and can be quantitatively captured through multimodal sensing technologies. Upon entering an exhibition, visitors do not engage with artworks in isolation; instead, they sequentially interact with entrance guidance, zone signage, artwork labels, route transitions, and interactive prompts. When a wayfinding visual communication system lacks sufficient information hierarchy, color contrast, typographic readability, or symbol consistency, visitors must expend greater visual-search effort. This increased cognitive load can be objectively reflected in sensor-derived metrics such as a prolonged time to first fixation (TFF), increased fixation counts, irregular scan paths, and higher revisit frequencies, ultimately leading to delayed navigation, interrupted comprehension, and accumulated exhibition fatigue.[1–3]

Jinshan peasant painting in Shanghai represents a distinctive regional visual-cultural resource characterized by vivid chromatic properties, decorative spatial composition, symbolic folk-art vocabulary, and strong narrative depictions of everyday life. From the viewpoint of materials and visual perception, its high color saturation and compositional density directly affect visual saliency and attention allocation, which are measurable through sensing technologies such as eye tracking and image-based saliency analysis. In recent years, Jinshan peasant painting has evolved from a localized folk-art form into a hybrid cultural medium with both exhibition and public-communication functions increasingly integrated with digital display systems and sensor-enabled interaction platforms.[4–6] When presented in museums, galleries, and public cultural spaces, its communicative effectiveness depends on not only intrinsic artistic features but also whether visitors can efficiently identify spatial zones, interpret thematic content, optimize navigation decisions, and construct coherent cognitive maps.

This dependence highlights the necessity of incorporating sensor-informed wayfinding systems, making Jinshan peasant painting exhibitions an appropriate case for investigating sensing-based visual communication strategies in intangible cultural heritage contexts. The conventional evaluation of exhibition wayfinding design typically relies on designers' experience, expert reviews, or subjective questionnaire-based assessments. Although these approaches provide valuable qualitative insights into aesthetics and usability, they lack the capability to capture fine-grained, real-time behavioral data, such as initial gaze allocation, dwell-time distribution, hesitation points, and adaptive responses to environmental variations. In contrast, sensor-based methodologies, particularly the integration of eye-tracking systems with context-aware sensing, enable objective and high-resolution measurement of visitor interaction processes. Eye-tracking technology can directly capture metrics such as TFF, fixation count, revisit frequency, scan path trajectory, and area-of-interest (AOI) attention ratios.

Meanwhile, context-aware sensors, including illuminance sensors, distance sensors, and crowd-density detection systems, provide complementary environmental data that affect visual perception and navigation behavior. Previous studies have demonstrated that virtual reality combined with eye-tracking techniques can effectively simulate and analyze wayfinding perception and signage comprehension,[7–9] while multimodal sensing approaches incorporating visitor exposure, saliency mapping, eye-movement data, and mobile eye-tracking systems offer deeper insights into engagement, attention distribution, and visual behavior in museum and exhibition environments.[10–16] On the basis of this background, in the present study, we establish a comprehensive evaluation model that integrates eye-tracking technology with context-aware sensing to systematically compare original and optimized wayfinding systems. The proposed framework incorporates both subjective and objective dimensions, including perceived usability, task performance, visual attention efficiency, and overall experiential quality, while further embedding environmental sensing parameters to enhance analytical robustness and reproducibility.

The objectives of this study are fourfold: (a) to construct an optimized, sensor-informed wayfinding framework tailored to the Jinshan peasant painting exhibition context; (b) to quantitatively verify whether the optimized design improves visual attention efficiency using eye-movement metrics; (c) to evaluate whether wayfinding optimization enhances navigation performance, content comprehension, and overall visitor experience; and (d) to analyze the effect of context-aware sensing variables such as lighting conditions, spatial distance, and crowd density on wayfinding effectiveness. Compared with previous studies, in this work, we not only preserve the cultural identity and visual-material characteristics of Jinshan peasant painting but also advance a verifiable and reproducible research framework grounded in sensing technologies and data-driven analysis. By integrating multisource sensor data with exhibition design evaluation, we contribute to the development of intelligent, adaptive, and evidence-based methodologies for optimizing intangible cultural heritage exhibitions, thereby bridging the gap between cultural presentation, human perceptual behavior, and sensor-enabled environmental interaction systems. Unlike conventional wayfinding studies that primarily rely on subjective evaluation or static design analysis, the proposed framework integrates eye-tracking sensing, context-aware environmental sensing, behavioral performance analysis, and synchronized multisource data acquisition to establish a quantitative and reproducible evaluation methodology. Although we adopt the Shanghai Jinshan peasant painting exhibition as the experimental context in the present study, the proposed sensing-based framework and optimization principles are also extendable to museums, galleries, smart exhibition environments, public guidance systems, and other intelligent wayfinding applications.

2. Data, Materials, and Methods

2.1 Research framework and hypotheses

In this study, the optimization of the wayfinding visual communication system was defined as the independent variable within a sensor-based evaluation framework. Visual attention efficiency and wayfinding task performance were treated as mediating indicators derived from objective sensing data, while exhibition understanding and overall experience were considered dependent variables reflecting high-level cognitive and affective responses. Context-aware sensing conditions were incorporated as environmental control and supplementary explanatory variables to account for dynamic influences on perception and behavior. From a sensing perspective, the rationale of this study is that improvements in typography, color contrast, graphic symbols, layout configuration, and information hierarchy will enhance the detectability and discriminability of key visual cues. In this study, key visual cues refer to major wayfinding guidance elements, including typographic hierarchy, color-band guidance, directional arrows and symbols, map/location indicators, and emphasized key-information regions designed to support rapid navigation and visual recognition within the exhibition environment. Such improvements are expected to be captured through eye-tracking metrics (e.g., reduced TFF, increased fixation efficiency, and simplified scan paths), thereby facilitating more efficient navigation and information acquisition. These performance gains are further hypothesized to translate into improved exhibition understanding, stronger cultural perception, and higher overall satisfaction. The hypothesized relationships among variables, integrating sensing-derived indicators and perceptual outcomes, are illustrated in Fig. 1.

2.2 Research design, participants, exhibition setting, and stimulus materials

A two-stage experimental design integrating multisource sensing technologies was adopted. Stage 1 focused on the construction, sensor-informed refinement, and pilot validation of the

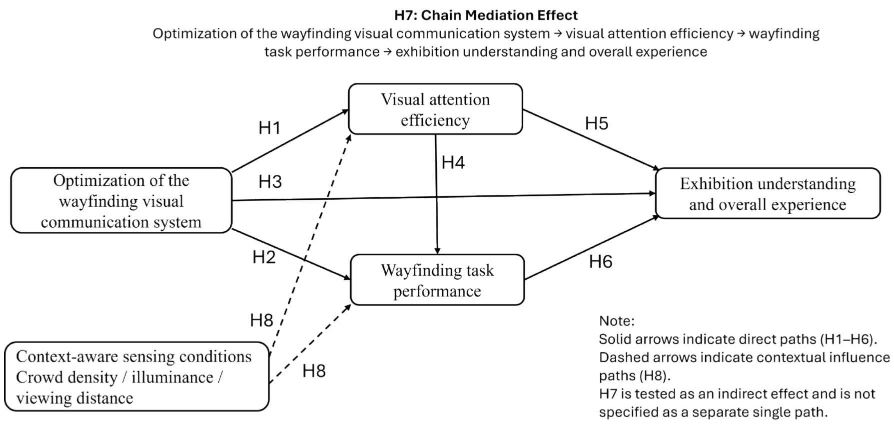


Fig. 1. Research model of the visual communication system for intangible cultural heritage exhibition wayfinding based on eye tracking and context-aware sensing.

wayfinding visual communication system. In this stage, preliminary eye-tracking data and observational feedback were used to iteratively adjust visual elements to ensure adequate perceptual saliency and readability. Stage 1 included design-principle review, expert consultation, and iterative pilot refinement. Rather than developing multiple alternative wayfinding models for selection, the optimized version was developed through the iterative refinement of the original wayfinding system. Specifically, the original system was progressively modified in accordance with design-principle review, expert consultation, and preliminary eye-tracking observations until the final optimized version satisfied the intended visual guidance and readability objectives. The design-principle review was based on prior studies related to exhibition wayfinding, visual hierarchy, color contrast, symbol consistency, and visual saliency. Expert consultation was conducted with five specialists from visual communication design, exhibition design, museum practice, and cultural heritage interpretation, who were recruited through purposive invitation and professional recommendation. In addition, 10 pilot participants were recruited to perform preliminary wayfinding tasks using the revised prototype. Preliminary eye-tracking observations and on-site feedback were used to identify delayed fixation, route confusion, visually overloaded regions, and insufficient attention to key information areas before the optimized version was finalized for Stage 2. Stage 2 consisted of a quasi-experimental comparison between the original and optimized wayfinding systems under controlled sensing conditions. The exhibition setting was established within either a physical exhibition environment or a high-fidelity simulated space, themed around Shanghai Jinshan peasant painting.

The spatial layout was organized into multiple thematic zones, including rural life, seasonal festivals, Jiangnan waterscapes, childhood memories, and everyday labor scenes in order to preserve the regional cultural context and visual characteristics. From a materials and perception standpoint, these zones provided diverse visual stimuli with varying levels of color saturation, compositional complexity, and semantic density, enabling the comprehensive evaluation of visual attention behavior under different conditions. The experiment was conducted at the Chinese Peasant Painting Village, Fengjing Town, Jinshan District, Shanghai, China. The experimental environment included both the exterior exhibition entrance and the interior exhibition space, allowing the realistic evaluation of visitor wayfinding behavior under practical exhibition conditions. Eye-movement data were collected using Tobii Pro Glasses 2 eye trackers (100 Hz sampling rate), while illuminance was measured using TES-1335 digital lux meters. Crowd density and viewing distance were also recorded during task execution as supplementary context-aware sensing variables. The two eye-tracking devices were assigned to participants during task execution, while the illuminance meters were positioned near major wayfinding task nodes, including the entrance overview area, exhibition-zone signage area, artwork-label area, interactive instruction area, and exit/service guidance area. The collected sensing and observational data were synchronized and integrated into a unified Excel-based processing platform for subsequent coding and statistical analysis.

The stimulus materials consisted of two sets of wayfinding visual communication designs. The original version followed a conventional signage design approach commonly observed in exhibition environments. In contrast, the optimized version was developed on the basis of sensor-informed design principles, including enhanced typographic hierarchy, structured color-band systems, consistent directional symbols, prioritized key information, and reduced visual interference through the simplified translation of local cultural imagery. Compared with the original wayfinding system, the optimized version introduced enhanced typographic hierarchy, color-band guidance, and consistent directional symbols and emphasized key information to improve visual recognition efficiency and reduce cognitive search load during navigation tasks. These design modifications were intended to improve the signal-to-noise ratio in visual perception and to facilitate rapid information extraction, as measurable through sensing metrics. Participants were recruited to perform a series of predefined wayfinding tasks while their behavioral and perceptual responses were recorded through integrated sensing systems. Specifically, eye-tracking devices were used to capture gaze-based indicators such as fixation duration, fixation count, revisit frequency, and scan path patterns. In parallel, context-aware sensing modules, including illuminance sensors, distance sensors, and crowd-density monitoring systems, were deployed to record environmental variables that may influence visual attention and navigation performance. The participant characteristics and the configuration of the five wayfinding tasks are summarized in Table 1. The overall experimental workflow, including sensor integration and data acquisition procedures, is illustrated in Fig. 2, while the design differences between the original and optimized wayfinding systems are presented in Fig. 3.

2.3 Research variables and data processing

The data used in this study were obtained from four integrated sources within a multisensor measurement framework: subjective scales, task-performance indicators, eye-tracking metrics, and context-aware sensing variables. This multimodal data structure enables the synchronized acquisition of perceptual, behavioral, and environmental information, thereby enhancing objectivity, reliability, and reproducibility. The subjective scales were designed to capture participants' perceived responses to the wayfinding system, including wayfinding clarity, reading and operational convenience, exhibition understanding, cultural perception and visual consistency, and overall experience and satisfaction. These measures were collected using a self-developed five-point Likert-scale questionnaire designed on the basis of previous studies related to exhibition wayfinding, visual communication, and visitor experience. Task-performance indicators were derived from behavioral observations and sensor-based tracking of participant movement. These indicators included completion time, path deviation count, error count, hesitation-event count, and task accuracy. In this study, hesitation events were operationally defined on the basis of combined thresholds of gaze stagnation and reduced movement velocity, enabling the objective identification of decision uncertainty during navigation tasks.

The subjective questionnaire used in this study was a self-developed five-point Likert-scale instrument designed to assess participants' perceptual and experiential evaluations of the wayfinding system. Each item was rated on a scale from 1 (strongly disagree) to 5 (strongly agree). The questionnaire consisted of five constructs: wayfinding clarity, reading and operational convenience, exhibition understanding, cultural perception and visual consistency, and overall experience and satisfaction, as shown in Table 2.

Table 1
Participant characteristics and task configuration.
(A) Participant characteristics

Category	Item	*n*	%	Description
Group	Original wayfinding system group	30	50.00	Assigned to the original wayfinding visual communication system
	Optimized wayfinding system group	30	50.00	Assigned to the optimized wayfinding visual communication system
Gender	Male	36	60.00	Participant demographic information
	Female	24	40.00	Participant demographic information
Age	Mean age	—	—	31.50 years (*SD* = 7.78; *range* = 20–48 years)
Education level	Junior college	7	11.67	Participant demographic information
	University	26	43.33	Participant demographic information
	Graduate school and above	21	35.00	Participant demographic information
	Missing	6	10.00	Missing education data
Vision status	Normal vision	22	36.67	Participant demographic information
	Corrected-to-normal vision	38	63.33	Participant demographic information
Design background	No	44	73.33	Whether the participant had a design-related background
	Yes	16	26.67	Whether the participant had a design-related background
Prior exhibition experience	No	34	56.67	Whether the participant had visited similar exhibitions
	Yes	26	43.33	Whether the participant had visited similar exhibitions

(B) Task configuration

Task No.	Task name	Corresponding wayfinding function	Task objective	Main measurement data
Task 1	Entrance identification and initial positioning	Entrance overview information	Identify entrance wayfinding information and confirm the starting position and exhibition entry point	Completion time, path deviation, error count, hesitation events, accuracy, TFF, AOI attention ratio, and scan path concentration
Task 2	Exhibition zone identification and theme positioning	Exhibition zone information	Identify zone locations and thematic categories and complete zone positioning	Completion time, path deviation, error count, hesitation events, accuracy, TFF, AOI attention ratio, and scan path concentration
Task 3	Artwork information acquisition	Artwork label information	Read artwork title, theme, and exhibition information and complete content acquisition	Completion time, path deviation, error count, hesitation events, accuracy, TFF, AOI attention ratio, and scan path concentration
Task 4	Interactive zone operation	Interactive prompt information	Complete the interactive-zone operation process and interpretation according to prompts	Completion time, path deviation, error count, hesitation events, accuracy, TFF, AOI attention ratio, and scan path concentration
Task 5	Exit and service location	Exit/service information	Locate the exit and related service positions and complete the final guidance task	Completion time, path deviation, error count, hesitation events, accuracy, TFF, AOI attention ratio, and scan path concentration

Note: A total of 60 valid participants were included, with 30 in the original wayfinding system group and 30 in the optimized wayfinding system group. The five tasks corresponded to different wayfinding functions related to entrance, zone, artwork, interaction, and exit/service information.

Eye-tracking metrics included TFF, total AOI dwell time, fixation count, revisit count, AOI attention ratio, scan path concentration, and heat-map concentration score. These indicators quantitatively describe visual attention allocation, information acquisition efficiency, and gaze distribution patterns across wayfinding elements. Context-aware sensing variables included crowd density, illuminance, and viewing distance, which were collected using integrated

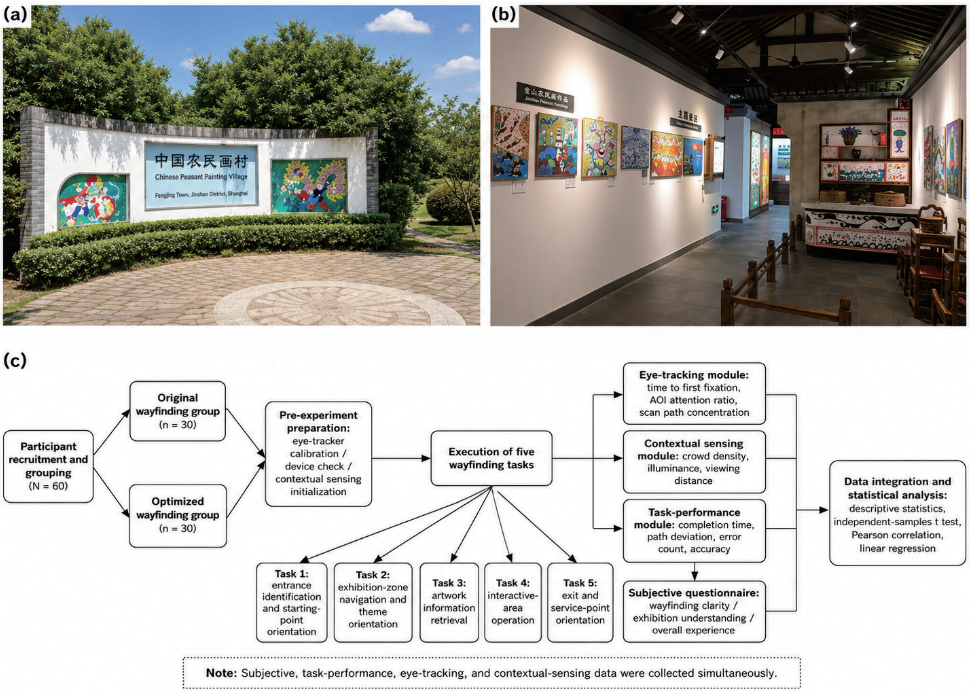
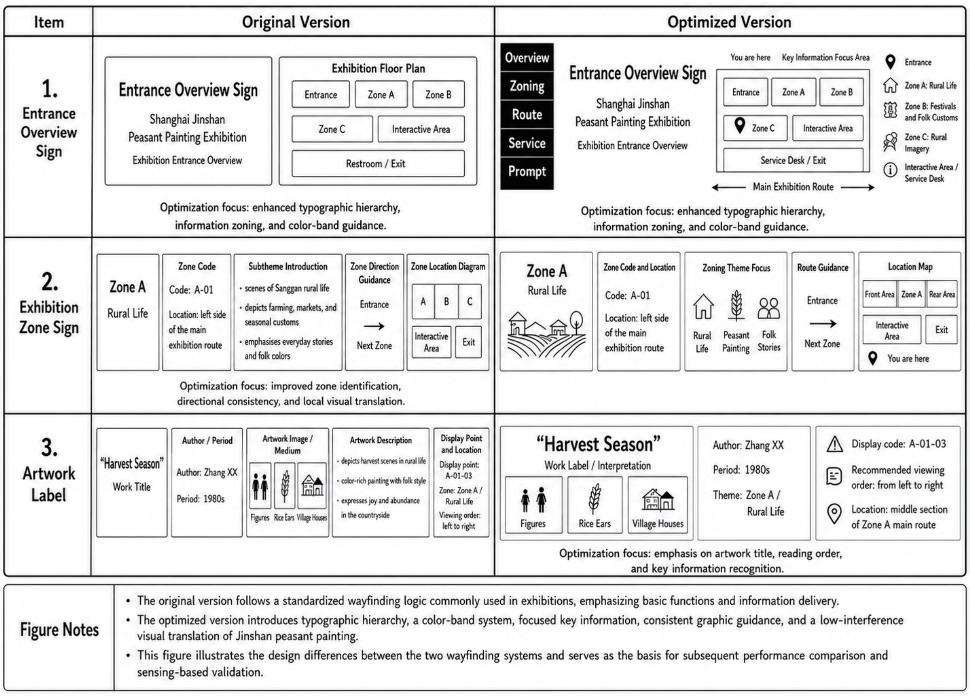
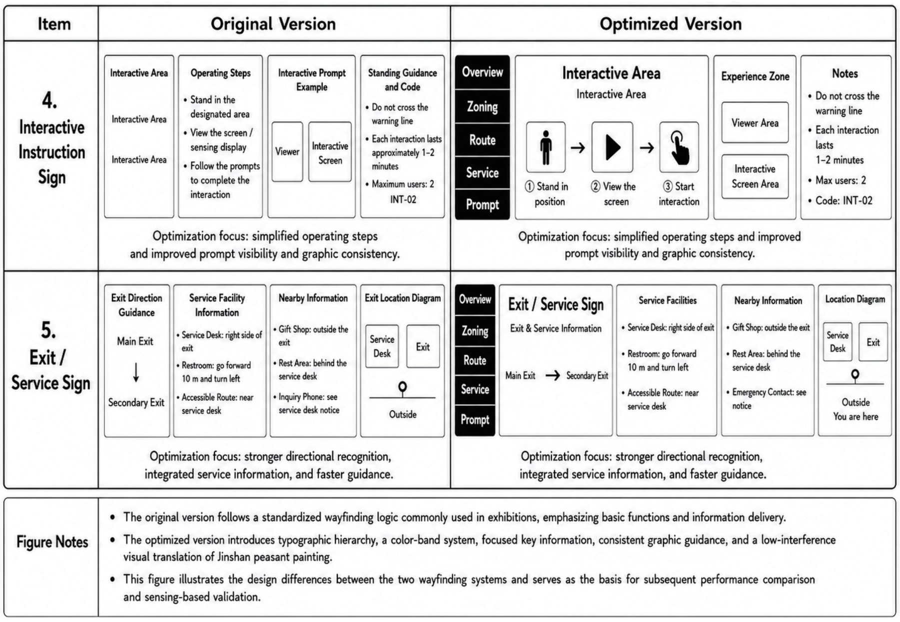


Fig. 2. (Color online) Experimental workflow, exhibition environment, and multisource sensing configuration used for eye-tracking and context-aware data acquisition: (a) exterior view of the experimental site, (b) interior exhibition environment used in the experiment, and (c) experimental workflow and sensing configuration.



(a)

Fig. 3. Original and optimized wayfinding visual communication designs.



(b)

Fig. 3. (Continued) Original and optimized wayfinding visual communication designs.

Table 2
Subjective questionnaire constructs and items.

Construct	Item code	Item statement	Response format
Wayfinding clarity	DC1	The wayfinding information was easy to identify.	5-point Likert scale
	DC2	The key information on the signs was clearly presented.	5-point Likert scale
	DC3	The information hierarchy of the signs was easy to understand.	5-point Likert scale
	DC4	The directional symbols and arrows were easy to interpret.	5-point Likert scale
	DC5	The route information was easy to follow.	5-point Likert scale
Reading and operational convenience	RO1	The text on the signs was easy to read.	5-point Likert scale
	RO2	The font size and layout were appropriate.	5-point Likert scale
	RO3	The information could be scanned quickly.	5-point Likert scale
	RO4	The operation/interaction instructions were easy to follow.	5-point Likert scale
	RO5	The amount of information was appropriate and not overloaded.	5-point Likert scale
Exhibition understanding	EU1	I could quickly understand the exhibition-zone information.	5-point Likert scale
	EU2	I could understand the theme of the artwork through the signage.	5-point Likert scale
	EU3	I could understand the relationship between the artwork and the exhibition zone.	5-point Likert scale
	EU4	The wayfinding system helped me know where to go next.	5-point Likert scale
	EU5	The wayfinding system helped me form a coherent understanding of the exhibition.	5-point Likert scale
Cultural perception and visual consistency	CP1	The visual design reflected the local cultural characteristics of Jinshan Peasant Painting.	5-point Likert scale
	CP2	The cultural visual elements did not interfere with readability.	5-point Likert scale
	CP3	The visual style of the wayfinding system was consistent across different nodes.	5-point Likert scale
	CP4	The visual design matched the exhibition theme well.	5-point Likert scale
	CP5	The wayfinding system enhanced the cultural atmosphere of the exhibition.	5-point Likert scale
Overall experience and satisfaction	OE1	The overall visiting process was smooth.	5-point Likert scale
	OE2	I experienced little confusion during navigation.	5-point Likert scale
	OE3	The wayfinding system improved my visiting efficiency.	5-point Likert scale
	OE4	The wayfinding system improved my overall exhibition experience.	5-point Likert scale
	OE5	Overall, I was satisfied with the wayfinding system.	5-point Likert scale

Note: All items were developed in-house for this study and rated on a five-point Likert scale ranging from 1 = strongly disagree to 5 = strongly agree.

environmental sensing modules. These variables characterize dynamic environmental conditions that may influence visual perception and navigation behavior and were incorporated as control or moderating factors in subsequent analyses. For regression analyses, three composite indicators were constructed to represent higher-level performance dimensions. Specifically, vae_total was derived from normalized eye-tracking metrics, taskperf_total was computed on the basis of standardized task-performance indicators, and exp_total was aggregated from subjective scale responses. Data preprocessing procedures included normalization, outlier removal, and indicator aggregation (with weighting where appropriate) to ensure comparability across participants and experimental conditions. The definitions of major variables, core indicators, and their calculation methods are summarized in Table 3.

Table 3
Research variables, indicators, and calculation methods.

Dimension	Variable name	Code	Observed indicators/components	Calculation method	Scoring direction
Independent variable	Wayfinding version	group_code	Original version = 0; optimized version = 1	Categorical coding	Higher values indicate the optimized version
Subjective evaluation	Wayfinding clarity	DC_mean	DC1–DC5	Mean of five items	Higher is better
	Exhibition understanding	EU_mean	EU1–EU5	Mean of five items	Higher is better
	Overall experience and satisfaction	OE_mean	OE1–OE5	Mean of five items	Higher is better
Composite subjective evaluation	Overall mean score	total_mean	DC_mean–OE_mean	Mean of five constructs	Higher is better
Task performance	Completion time	t1_time_sec–t5_time_sec	Completion time across five tasks (s)	Direct recording	Lower is better
	Task accuracy	t1_accuracy_pct–t5_accuracy_pct	Accuracy across five tasks (%)	Direct recording	Higher is better
Eye-tracking metric	TFF	t1_tff_sec–t5_tff_sec	TFF across five tasks	Direct recording	Lower is better
	AOI attention ratio	t1_aoi_pct–t5_aoi_pct	AOI attention ratio across five tasks	Direct recording	Higher is better
	Scan path concentration	t1_scan_pct–t5_scan_pct	Scan-path concentration across five tasks	Direct recording	Higher is better
Composite indicator	Visual attention efficiency total score	vae_total	TFF, revisit count, AOI attention ratio, scan path concentration, and heat-map concentration	Standardized and averaged after directional adjustment	Higher is better
	Wayfinding task performance total score	taskperf_total	Completion time, path deviation, error count, hesitation events, and accuracy	Standardized and averaged after directional adjustment	Higher is better
	Exhibition understanding and overall experience total score	exp_total	EU_mean, OE_mean	Standardized and averaged	Higher is better

Note: All subjective constructs were measured using a five-point Likert scale. vae_total, taskperf_total, and exp_total were the core composite indicators used in the subsequent linear regression analyses.

2.4 AOI definition, experimental procedure, and statistical analysis

AOIs were defined in accordance with the functional structure of the wayfinding visual communication system, including title areas, key-information areas, guidance/map areas, and service-information areas. This structured AOI segmentation enabled the extraction and calculation of core eye-tracking indicators, including TFF, AOI attention ratio, scan path concentration, and heat-map concentration. From a sensing perspective, AOI delineation was aligned with the spatial distribution of visual stimuli and calibrated to ensure consistency between gaze coordinates and display regions, thereby improving the accuracy of attention mapping and data interpretation. After participant recruitment and grouping, each participant first underwent eye-tracker calibration and device validation to ensure data accuracy and stability. The calibration procedure followed a standard multipoint protocol to minimize spatial error in gaze estimation. Participants then performed five predefined wayfinding tasks under the assigned version of the wayfinding system (original or optimized). During task execution, eye-tracking data, context-aware sensing data, and task-performance data were synchronously collected through an integrated sensing system.

Eye-movement signals were continuously recorded to capture gaze behavior, while environmental sensors monitored contextual variables such as illuminance, spatial distance, and crowd density. Movement-related data were also logged to support the derivation of task-performance indicators. Upon completion of all tasks, participants filled out the subjective questionnaire to report their perceptual and experiential evaluations. The statistical analyses consisted of descriptive statistics, independent-participants *t*-tests, Pearson correlation analysis, and linear regression analysis to examine relationships among sensing-derived indicators and subjective outcomes. Prior to analysis, all data were preprocessed through normalization and consistency checks to ensure comparability across participants and experimental conditions. The integration of multisource sensing data allowed for cross-validation between behavioral performance, visual attention metrics, and environmental variables, thereby strengthening the robustness of the analytical framework. The principles used to define AOIs and representative eye-tracking output formats are illustrated in Fig. 4.

To make the regression analysis easier to understand, three linear regression models were established in accordance with the conceptual framework of the study. Model 1 examined whether the wayfinding version and contextual sensing conditions predicted visual attention efficiency (vae_total). Model 2 examined whether the wayfinding version, contextual sensing conditions, and visual attention efficiency predicted wayfinding task performance (taskperf_total). Model 3 examined whether the wayfinding version, visual attention efficiency, and wayfinding task performance predicted exhibition understanding and overall experience (exp_total). Thus, the three models were constructed progressively from perceptual and behavioral indicators to higher-level experiential outcomes.

2.5 Ethics and data quality control

Because this study involved the collection of visual behavior, movement-related responses, and subjective evaluations from human participants, informed consent was obtained prior to the

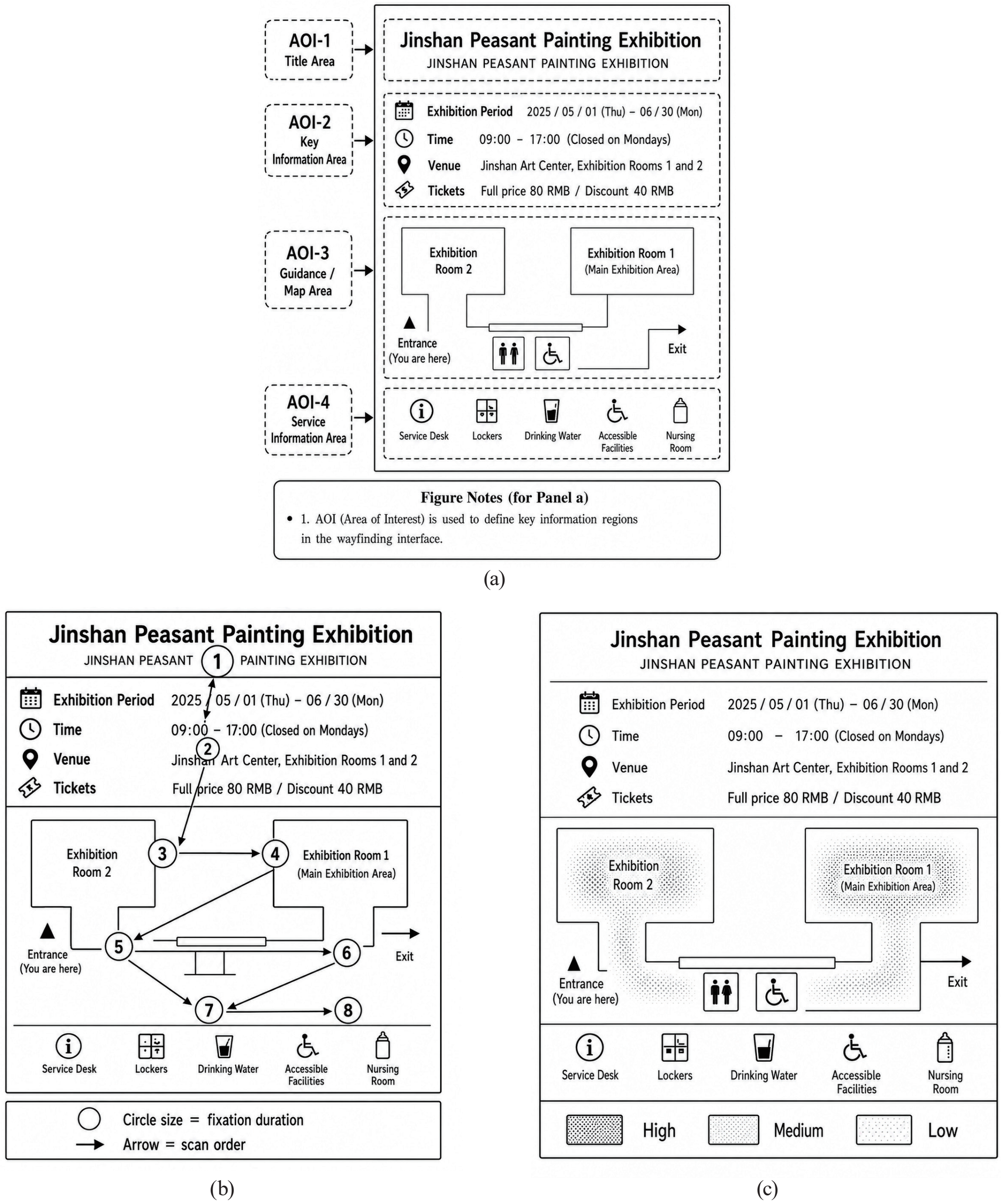


Fig. 4. Definition of AOI and representative eye-tracking outputs. (a) AOI definition, (b) eye-tracking scan-path, and (c) heat map distribution.

formal experiment, and all data were anonymized to ensure participant privacy and confidentiality. The experimental procedures complied with general ethical standards for human-subject research. In the data preprocessing stage, eye-tracking data were time-synchronized with task-performance and context-aware sensing data to ensure temporal consistency across multiple data sources. The gaze data were then aligned with predefined AOIs for subsequent analysis. Data quality control procedures included screening for outliers and invalid participants to reduce the influence of head movement, signal loss, occlusion, and variations in ambient lighting conditions. Only valid and stable data segments were retained to ensure the reliability and accuracy of the final analysis.

3. Results

3.1 Descriptive statistics

A total of 60 valid participants were included in the analysis, with 30 participants assigned to the original-version group and 30 to the optimized-version group. All data were obtained within an integrated sensing framework, ensuring the synchronized acquisition of subjective responses, behavioral performance, eye-tracking metrics, and context-aware environmental variables. For the subjective scales, mean scores ranged from 3.700 to 3.937, with an overall mean of 3.787, indicating a generally positive perception of the wayfinding system across participants. These results suggest that both system versions achieved acceptable levels of usability and experiential quality, as reflected in participant-reported evaluations. For task-performance indicators derived from sensor-based movement tracking, the mean completion times across the five tasks ranged from 40.663 to 75.908 s, with Task 4 showing the highest mean completion time, indicating higher navigation complexity. Likewise, the mean task accuracy values across the five tasks ranged from 86.740 to 91.245%. For the core eye-tracking metrics, the mean time-to-first-fixation values across tasks ranged from 1.908 to 2.498 s, the mean AOI attention ratios across tasks ranged from 66.640 to 70.422%, and the mean scan path concentration values across tasks ranged from 69.475 to 71.155%. These indicators, obtained from gaze-sensing data, collectively reflect the efficiency and stability of visual attention allocation within the wayfinding system. The descriptive statistics of all major variables, including sensing-derived indicators and subjective measures, are summarized in Table 4.

3.2 Group differences between the original and optimized versions

The independent-participant *t*-test results based on multisource sensing data indicated that the optimized version outperformed the original version across subjective evaluation, task performance, and eye-tracking metrics. For the subjective scales, wayfinding clarity, exhibition understanding, and the overall mean score showed statistically significant differences, with very large effect sizes, indicating improved perceived usability and experience under the optimized design. For task-performance indicators derived from sensor-based movement tracking, the optimized version significantly reduced completion time and improved task accuracy across all five tasks, demonstrating enhanced navigation efficiency and decision effectiveness. For eye-tracking metrics, the optimized version significantly shortened TFF and increased AOI attention ratio and scan path concentration. These results indicate that participants were able to locate key wayfinding information more rapidly and exhibited more focused and structured visual-search behavior under the optimized condition. The detailed statistical results are summarized in

Table 4
Descriptive statistics of major variables.

Dimension	Variable name	Code	Mean (M)	Standard deviation (SD)
Subjective evaluation	Wayfinding clarity	DC_mean	3.763	0.477
	Reading and operational convenience	RO_mean	3.787	0.533
	Exhibition understanding	EU_mean	3.937	0.462
	Cultural perception and visual consistency	CP_mean	3.700	0.569
	Overall experience and satisfaction	OE_mean	3.750	0.543
	Overall mean score	total_mean	3.787	0.446
Task performance	Task 1 completion time (s)	t1_time_sec	40.663	7.550
	Task 3 completion time (s)	t3_time_sec	64.295	10.630
	Task 5 completion time (s)	t5_time_sec	47.860	7.826
	Task 1 accuracy (%)	t1_accuracy_pct	91.245	6.870
	Task 3 accuracy (%)	t3_accuracy_pct	90.055	6.433
	Task 5 accuracy (%)	t5_accuracy_pct	89.883	6.739
Core eye-tracking metrics	Task 1 TFF (s)	t1_tff_sec	1.908	0.613
	Task 3 AOI attention ratio (%)	t3_aoi_pct	70.422	7.537
	Task 3 scan path concentration (%)	t3_scan_pct	71.087	8.688

Note: This table presents a concise summary of representative descriptive statistics for the main-text discussion. Only selected subjective-evaluation variables, task-performance indicators, and core eye-tracking metrics are included; therefore, not every value discussed in the text appears in this table.

Table 5, while task-performance and eye-tracking metrics are presented graphically in Figs. 5 and 6, respectively.

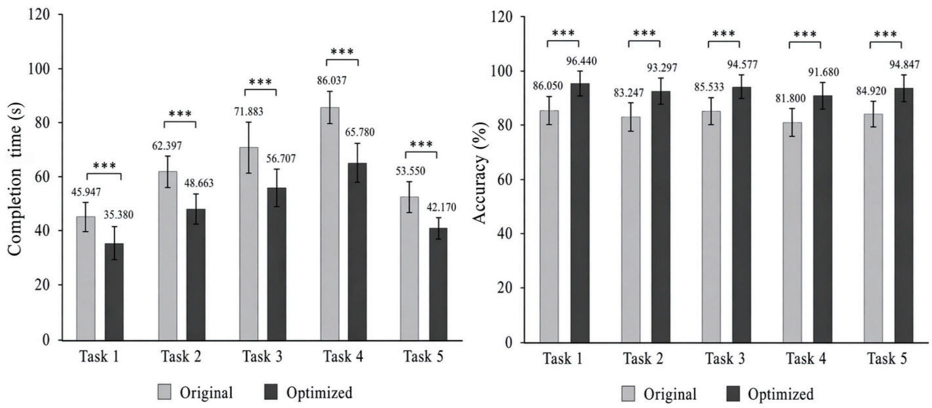
3.3 Correlation analysis

The Pearson correlation analysis, conducted on integrated multisource sensing data, revealed a clear and consistent association structure among the main variables. For the subjective scales, wayfinding clarity, exhibition understanding, and overall experience were all significantly positively correlated and were also strongly correlated with the overall mean score, indicating internal consistency in participants' perceptual evaluations. For the eye-tracking metrics, TFF showed significant negative correlations with AOI attention ratio and scan path concentration, suggesting that shorter initial fixation times were associated with more efficient and concentrated visual attention. In contrast, AOI attention ratio and scan path concentration were significantly positively correlated, indicating coherent and stable gaze-allocation patterns captured by the eye-tracking system. For task-performance indicators derived from sensor-based behavioral tracking, completion time and task accuracy were significantly negatively correlated, demonstrating that faster task execution was generally associated with higher accuracy. Cross-dimensional analysis further indicated that improved eye-tracking performance and enhanced task performance were generally associated with higher subjective evaluation scores. This finding highlights the consistency between objective sensing-derived indicators and subjective perception outcomes. The main correlation results are presented in Table 6.

Table 5
Independent-participant *t*-test results for the original and optimized wayfinding systems.

Dimension	Variable	Original version $M(SD)$	Optimized version $M(SD)$	t	df	p	Cohen's d
Subjective evaluation	Wayfinding clarity (DC_mean)	3.387 (0.319)	4.140 (0.258)	−10.052	58	< 0.001	−2.595
	Exhibition understanding (EU_mean)	3.560 (0.231)	4.313 (0.296)	−10.992	58	< 0.001	−2.838
	Overall mean score (total_mean)	3.363 (0.142)	4.212 (0.109)	−25.913	58	< 0.001	−6.691
Task performance	Task 1 completion time (t1_time_sec)	45.947 (6.301)	35.380 (4.302)	7.586	58	< 0.001	1.959
	Task 3 completion time (t3_time_sec)	71.883 (7.293)	56.707 (7.586)	7.899	58	< 0.001	2.040
	Task 5 completion time (t5_time_sec)	53.550 (4.837)	42.170 (5.851)	8.211	58	< 0.001	2.120
	Task 1 accuracy (t1_accuracy_pct)	86.050 (5.402)	96.440 (3.314)	−8.979	58	< 0.001	−2.318
	Task 3 accuracy (t3_accuracy_pct)	85.533 (5.052)	94.577 (4.047)	−7.652	58	< 0.001	−1.976
	Task 5 accuracy (t5_accuracy_pct)	84.920 (4.165)	94.847 (4.908)	−8.447	58	< 0.001	−2.181
Eye-tracking metrics	Task 1 TFF (t1_tff_sec)	2.410 (0.344)	1.407 (0.354)	11.109	58	< 0.001	2.868
	Task 3 TFF (t3_tff_sec)	3.076 (0.364)	1.920 (0.320)	13.062	58	< 0.001	3.373
	Task 5 TFF (t5_tff_sec)	2.482 (0.374)	1.531 (0.333)	10.413	58	< 0.001	2.689
	Task 1 AOI attention ratio (t1_aoi_pct)	58.197 (5.580)	72.937 (4.727)	−11.040	58	< 0.001	−2.851
	Task 3 scan path concentration (t3_scan_pct)	63.717 (4.368)	78.457 (4.703)	−12.578	58	< 0.001	−3.248

Note: Lower values indicate better performance for completion time and TFF. Higher values indicate better performance for accuracy, AOI attention ratio, and scan path concentration.



Note: Bars indicate means; error bars indicate standard deviations; *** $p < .001$.

(a) (b)

Fig. 5. Task performance using original and optimized wayfinding systems: (a) task completion time across five tasks and (b) task accuracy across five tasks.

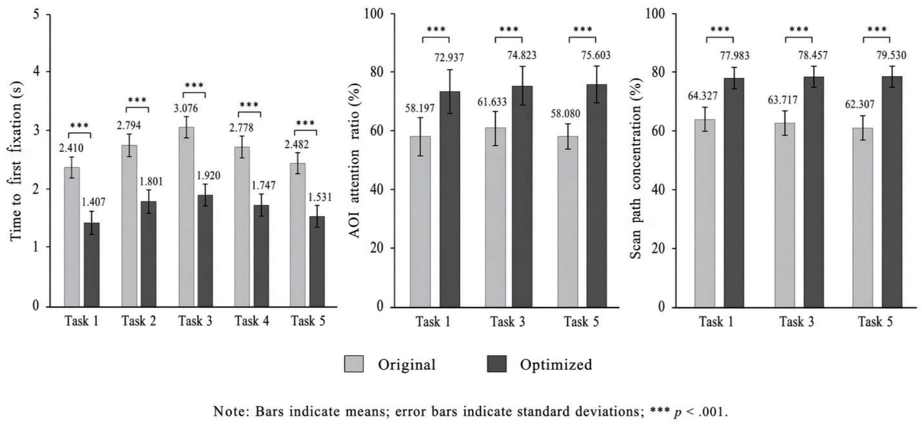


Fig. 6. Key eye-tracking metrics for original and optimized wayfinding systems: (a) TFF across five tasks, (b) AOI attention ratio, and (c) scan path concentration.

Table 6
Pearson correlation results among major subjective, task-performance, and eye-tracking variables.

Variable 1	Variable 2	Pearson's *r*	*p*
Wayfinding clarity (DC_mean)	Exhibition understanding (EU_mean)	0.703	< 0.001
Wayfinding clarity (DC_mean)	Overall experience and satisfaction (OE_mean)	0.671	< 0.001
Exhibition understanding (EU_mean)	Overall mean score (total_mean)	0.857	< 0.001
TFF in Task 1 (t1_tff_sec)	AOI attention ratio in Task 1 (t1_aoi_pct)	−0.666	< 0.001
TFF in Task 1 (t1_tff_sec)	Scan path concentration in Task 1 (t1_scan_pct)	−0.695	< 0.001
AOI attention ratio in Task 1 (t1_aoi_pct)	Scan path concentration in Task 1 (t1_scan_pct)	0.710	< 0.001
Completion time in Task 1 (t1_time_sec)	Accuracy in Task 1 (t1_accuracy_pct)	−0.601	< 0.001
Completion time in Task 3 (t3_time_sec)	Accuracy in Task 3 (t3_accuracy_pct)	−0.453	< 0.001
TFF in Task 1 (t1_tff_sec)	Overall mean score (total_mean)	−0.820	< 0.001
AOI attention ratio in Task 1 (t1_aoi_pct)	Overall mean score (total_mean)	0.802	< 0.001
Completion time in Task 1 (t1_time_sec)	Overall mean score (total_mean)	−0.671	< 0.001
Accuracy in Task 3 (t3_accuracy_pct)	Overall mean score (total_mean)	0.722	< 0.001

Note: Only the correlation coefficients that best represent the core hypotheses and the association structure of the variables are retained in the main text.

3.4 Linear regression analysis

All three linear regression models, established on the basis of integrated-sensing-derived indicators, were statistically significant, indicating that the proposed predictive framework has satisfactory explanatory power for visual attention efficiency, wayfinding task performance, and exhibition understanding/overall experience. Model 1 explained 97.8% of the variance in vae_total, Model 2 explained 90.6% of the variance in taskperf_total, and Model 3 explained 81.6% of the variance in exp_total. These results demonstrate that the combination of eye-tracking metrics, task-performance indicators, and context-aware sensing variables provides strong predictive capability for both behavioral and perceptual outcomes. Across all three models, the most stable and significant predictor was group_code (1), indicating that the optimized wayfinding system, compared with the original version, had significant positive effects on visual attention efficiency, task performance, and overall experience. Such effects reflect the effectiveness of sensor-informed design optimization in improving both objective performance metrics and subjective evaluation outcomes. The overall parameter estimates and model summaries for the three regression models are presented in Table 7.

4. Discussion

The results consistently showed that the optimized wayfinding system outperformed the original version across subjective evaluation, task performance, and sensing-derived eye-tracking metrics. From a multisource sensing perspective, this improvement is reflected in the convergence of perceptual evaluations, behavioral outcomes, and gaze-based indicators. First, the significant differences in the subjective scales indicated that the optimized version enhanced information-hierarchy recognition, usability, exhibition understanding, cultural perception, and overall experience. Second, sensor-recorded behavioral data showed that the optimized version significantly shortened completion time and increased task accuracy across all five tasks, demonstrating that wayfinding optimization produces stable and practically meaningful improvements in navigation efficiency rather than merely superficial visual enhancement. Third, the eye-tracking results revealed that the optimized version enabled participants to identify key information more rapidly (shorter TFF) and maintain more concentrated gaze distributions within AOIs and core visual hotspots, indicating more efficient visual attention allocation and clearer route organization.

Table 7
Linear regression results for visual attention efficiency, wayfinding task performance, and exhibition understanding/overall experience.

Model	Dependent Variable	Main Significant Independent Variable	*R*	R^2	Adjusted R^2	*F*	*B*	*t*	*p*
Model 1	Visual attention efficiency total score (vae_total)	group_code (1)	0.989	0.978	0.976	612.862	1.526	48.618	< 0.001
Model 2	Wayfinding task performance total score (taskperf_total)	group_code (1)	0.952	0.906	0.898	104.577	0.948	3.559	< 0.001
Model 3	Exhibition understanding and overall experience total score (exp_total)	group_code (1)	0.904	0.816	0.807	83.044	2.211	2.830	0.006

Note: Across the three regression models, group_code (1) remained the most stable significant predictor. Because group_code (1) was treated as a dummy-coded categorical contrast, the unstandardized coefficient (B), *t* statistic, and *p* value are reported. Context-aware sensing variables and composite intermediate indicators did not show stable additional significant effects in the current dataset.

The correlation analysis further demonstrated that improved eye-tracking performance and enhanced task performance were generally associated with higher subjective evaluations, indicating strong consistency among sensing indicators, behavioral performance, and visitor experience. This consistency supports the theoretical pathway proposed in this study, in which wayfinding optimization influences subjective experience through improvements in visual attention efficiency and task performance. Within this framework, eye-tracking metrics serve not only as descriptive representations of visual behavior but also as functional sensing indicators capable of quantifying the effectiveness of wayfinding systems. This interpretation aligns with prior eye-tracking studies in museum and exhibition contexts.[11–13] However, the regression analysis indicated that the wayfinding version was the most stable and significant predictor across all three models, whereas context-aware sensing variables and composite intermediate indicators did not exhibit consistent additional predictive effects.

This suggests that the optimization of the wayfinding system itself accounted for a substantial proportion of the explainable variance, thereby reducing the observable independent contributions of environmental sensing variables within the current analytical framework. This finding does not imply that contextual sensing factors or mediation mechanisms are negligible; rather, it indicates that system-level design differences constituted the dominant influence under the present experimental conditions. It is also possible that the selected environmental variables (e.g., illuminance, viewing distance, and crowd density) exhibited limited variability within the controlled experimental setting, thereby constraining their explanatory power. From a methodological perspective, these findings highlight the importance of integrating high-resolution sensing data with appropriate analytical models to capture complex interaction effects. Several limitations should also be noted. First, the current experiment was conducted within a relatively controlled exhibition environment and involved a limited participant size, which may constrain the generalizability of the findings. Second, only selected context-aware sensing variables, including illuminance, viewing distance, and crowd density, were incorporated in the present framework. More dynamic sensing conditions and multimodal physiological signals may provide deeper insight into visitor behavior and cognitive responses. In addition, although the proposed framework demonstrated stable performance under the current experimental conditions, further validation in larger-scale museums, public guidance systems, and smart exhibition environments remains necessary. Future research will therefore be focused on integrating additional sensing technologies, expanding environmental variability, and applying more advanced analytical models to improve system adaptability and analytical robustness.

Future research should include more fine-grained task-level sensing indicators, dynamic interaction measures, or advanced analytical approaches such as structural equation modeling to further examine the causal pathways and mediation mechanisms involved. In addition, expanding the range and variability of context-aware sensing conditions may help reveal more nuanced environmental effects on wayfinding performance and visual attention. Overall, this study, we demonstrated that an exhibition wayfinding system can be conceptualized as a sensing-integrated application system whose performance is measurable, optimizable, and verifiable through quantitative data. By combining eye-tracking technology with context-aware sensing, the proposed framework provides a systematic and reproducible approach for evaluating visual communication effectiveness and user interaction processes. For applications in intangible cultural heritage exhibitions, museum guidance systems, and smart cultural-display environments, this approach offers both practical implementation value and methodological rigor, while aligning with the broader trend of employing sensing technologies to support interaction, localization, and intelligent guidance in cultural settings.[16] Although in the present study, we did not propose a new hardware sensor, the proposed framework provides practical sensing logic and measurable evaluation indicators for future sensor-assisted exhibition systems. The integration of eye tracking, environmental sensing, and behavioral analysis also highlights the potential for the future development of adaptive signage interfaces, context-aware guidance systems, and intelligent multisensor exhibition platforms.

5. Conclusions

Using the Shanghai Jinshan peasant painting exhibition as a case study, we proposed a sensor-integrated evaluation model for wayfinding visual communication that combines eye-tracking metrics, context-aware sensing variables, task-performance indicators, and subjective assessment. Within this multisource sensing framework, the results consistently confirmed that the optimized wayfinding system significantly outperformed the original version in subjective scales, task performance, and core eye-tracking metrics. These findings indicate that the optimized design can effectively enhance the recognition of key information, improve task-completion quality, and strengthen the overall exhibition experience, while providing measurable evidence from both behavioral and perceptual dimensions. The contributions of this study can be summarized in three aspects. First, we established a measurable and reproducible evaluation methodology for exhibition wayfinding based on integrated sensing technologies, enabling the systematic acquisition and analysis of visual attention, behavioral performance, and environmental context. Second, we provided objective evidence, derived from eye-tracking data and sensor-based task-performance indicators, to validate the effectiveness of wayfinding visual communication optimization, thereby bridging the gap between design intervention and quantitative performance assessment. Third, we proposed an integrated analytical framework that can be extended to applications in intangible cultural heritage exhibitions, museum guidance systems, and smart cultural-display environments, supporting data-driven design and evaluation processes. Future research may include further expansion of the participant size, incorporation of additional multimodal sensing data (such as physiological or motion-based signals), and refinement of the analytical framework through mediation analysis, interaction modeling, or structural equation modeling. Such extensions would allow deeper investigation of the mechanisms underlying wayfinding optimization and enhance the generalizability of sensor-based evaluation approaches in complex exhibition environments.

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