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Sensor-enabled Three-dimensional Presentation and Interaction Modeling for Mobile Augmented Reality Advertising: A Measurement and Structural Validation Approach

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Mobile augmented reality (AR) advertising has emerged as a sensor-integrated application combining smartphone-based visual sensing, motion tracking, and interactive feedback to deliver immersive experiences. However, limited attention has been paid to how sensing-driven three-dimensional (3D) presentation and interaction jointly affect user perception and behavior from a measurement perspective. In this study, we aim to develop and validate a sensor-enabled structural evaluation framework for mobile AR advertising by examining the relationships among seven constructs: 3D presentation quality, interaction quality, perceived informativeness, immersion, perceived ease of use, attitude toward the advertisement, and usage intention. In this study, we propose a sensor-enabled structural evaluation framework linking 3D presentation and interaction qualities—derived from mobile sensing and rendering processes—to perceived informativeness, immersion, perceived ease of use, attitude, and usage intention. A questionnaire with 28 items across seven constructs was administered after a mobile AR task, yielding valid responses from 350 participants. The measurement model demonstrated satisfactory reliability, validity, and overall fit. Structural equation modeling results indicate that 3D presentation quality significantly enhances perceived informativeness, while interaction quality improves perceived ease of use. Perceived informativeness and immersion positively affect attitude, and both perceived ease of use and attitude increase usage intention. Mediation analysis further confirms that perceived informativeness, perceived ease of use, and attitude act as key transmission pathways. These findings suggest that the effectiveness of mobile AR advertising depends on not only technology deployment but also how sensor-generated information is transformed into clear and responsive user experiences. In this study, we contribute a validated framework linking sensing mechanisms, perceptual processes, and behavioral outcomes, and

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highlight the importance of optimizing sensor responsiveness and information representation in AR systems. However, the result of this study was limited to a smartphone-based AR prototype and a questionnaire-based cross-sectional evaluation conducted within a controlled experimental environment. In addition, engineering-level sensing indicators such as tracking error, registration stability, and system latency were not directly incorporated into the structural model. Future studies will therefore focus on integrating objective sensing-performance metrics, multimodal interaction data, and more diverse AR application scenarios to establish a more comprehensive sensor-enabled evaluation framework for immersive interactive systems.

1. Introduction

1.1 Background of mobile augmented reality (AR) advertising

With the rapid advancement of smartphone computing power, computer vision, and mobile sensing technologies, AR has evolved from a display-oriented technology into a practical platform for retail, advertising, and interactive communication. Modern smartphones integrate multiple sensing modalities, including camera-based visual perception, inertial measurement units (IMUs), and real-time environmental tracking, enabling AR systems to accurately align virtual objects with physical environments. In practical mobile AR systems, the primary sensing components are integrated directly into the smartphone hardware platform. The rear RGB camera is used to continuously capture environmental images and extract visual feature points for scene recognition and spatial mapping. Simultaneously, the IMU consisting of an accelerometer and a gyroscope measures device movement, orientation variation, and rotational velocity signals. These sensing signals are fused through visual–inertial odometry algorithms to estimate the relative position and pose of the smartphone in real time. On the basis of the obtained spatial coordinates and plane-detection results, the AR engine constructs a three-dimensional (3D) coordinate system in which virtual advertising objects can be anchored to physical surfaces. The rendered 3D content is then continuously updated according to user movement and viewpoint changes, enabling stable spatial alignment and interactive visualization. From a sensing perspective, the effectiveness of mobile AR advertising therefore depends on the integration of environmental perception, motion sensing, coordinate estimation, and real-time rendering processes.

In mobile AR advertising, virtual 3D content can be seamlessly overlaid onto real-world scenes, allowing users to not only passively receive information but also actively explore products through direct interaction in a situated context.(1,2) This interaction is supported by sensing-driven processes such as spatial mapping, motion tracking, and real-time rendering, which collectively transform raw environmental data into perceivable visual and interactive stimuli. In addition, continuous advancements in mobile processors and graphics capabilities have further improved the stability and responsiveness of AR systems, enabling more realistic visualization and smoother user interaction. Consequently, mobile AR advertising should not be regarded merely as an extension of conventional digital advertising, but rather as a sensor-enabled interactive system that integrates 3D presentation, environmental alignment, and user operation.(3–5) The effectiveness of such systems depends on not only visual quality but also the coordination among sensing accuracy, system latency, and rendering performance. When these components are well integrated, AR advertising can provide users with context-aware, interactive, and information-rich experiences that go beyond traditional media formats.

1.2 Research gap and study objectives

Although previous studies have demonstrated that AR advertising can improve brand attitude, user engagement, and purchase-related responses, existing research has predominantly emphasized outcome variables while paying relatively limited attention to the underlying system-level mechanisms.(6) In particular, the roles of sensing-driven presentation and interaction processes have not been sufficiently examined from a structured measurement perspective.(7) Most previous work treats AR experience as a holistic construct, without explicitly distinguishing between 3D presentation and interaction qualities as two fundamental system components. However, from an engineering standpoint, these components originate from different sensing and processing pipelines. 3D presentation quality is largely affected by rendering fidelity, spatial registration accuracy, and visual realism, whereas interaction quality depends on sensor responsiveness, gesture recognition accuracy, and system feedback latency.(8)

Moreover, these two components may affect user perception through different cognitive pathways, leading to distinct impacts on information processing, usability evaluation, and affective response. Therefore, a systematic investigation of how these two dimensions jointly affect user perception and behavioral responses remains necessary. Compared with previous AR advertising and technology-acceptance studies, the novelty of this study lies in three aspects. First, we explicitly separate 3D presentation and interaction qualities as two independent sensing-driven system dimensions rather than treating AR experience as a single holistic construct. Second, the proposed framework establishes a structured relationship among sensing-related system performance, perceptual evaluation, and behavioral intention through a validated SEM-based measurement model. Third, unlike conventional AR marketing studies that mainly emphasize consumer response outcomes, in this study, we integrate sensing concepts, spatial tracking mechanisms, and interaction responsiveness into the evaluation framework, thereby linking engineering-level sensing processes with user-centered behavioral analysis. These characteristics distinguish the present work from the existing AR usability and advertising studies, and provide a measurement-oriented contribution for sensor-enabled interactive systems.

In this study, we aim to develop and validate a sensor-enabled structural model for mobile AR advertising. Beyond user-experience evaluation, the proposed framework also provides implications for future sensor and sensing-system development in mobile AR environments. By identifying how sensing-related factors such as spatial tracking stability, interaction responsiveness, and rendering alignment affect perceptual and behavioral outcomes, we established a measurement-oriented relationship between sensor-system performance and user cognition. Such findings may support the future design of low-latency motion sensors, vision-based spatial tracking modules, multimodal sensing integration systems, and sensor-responsive display materials for interactive AR applications. Therefore, the contribution of this study is not only limited to behavioral analysis, but also extends to the evaluation and optimization of next-generation sensing technologies for immersive mobile systems. Specifically, it examines how 3D presentation and interaction qualities affect perceived informativeness, immersion, perceived ease of use, attitude toward the advertisement, and usage intention, thereby bridging the gap between sensing mechanisms and user-centered evaluation, and providing a measurement-oriented framework for AR system assessment.

1.3 Conceptual model and hypotheses

On the basis of the identified research gap, we propose a structural model in which 3D presentation and interaction qualities function as system-level antecedents.(9) Perceived informativeness, immersion, and perceived ease of use are modeled as cognitive and affective mediators, while attitude toward the advertisement and usage intention are treated as outcome variables. From a sensing perspective, the proposed model represents a multi-stage transformation process in which sensor-generated environmental data are first captured through perception modules (e.g., camera sensing and motion tracking), then processed through rendering and interaction mechanisms, and finally translated into perceptual stimuli experienced by users.(10) These stimuli are subsequently interpreted through cognitive evaluation (e.g., informativeness and ease of use) and affective response (e.g., immersion), which together shape overall attitude and behavioral intention.

Compared with conventional advertising evaluation models, this framework explicitly incorporates sensing-driven system attributes as upstream determinants, thereby linking engineering-level system performance with user-level perceptual outcomes. In this context, 3D presentation quality reflects the effectiveness of visual reconstruction and spatial alignment, whereas interaction quality captures the responsiveness and usability of the sensing–feedback loop.(11) By modeling these constructs separately, we aim to clarify their distinct functional roles and their contributions to different stages of user response formation. To empirically validate the proposed framework, eight hypotheses are formulated to examine both the direct and indirect relationships among these constructs. These hypotheses collectively test whether sensing-enabled presentation and interaction processes affect behavioral intention through structured cognitive and affective pathways, thereby providing empirical support for a measurement-based understanding of mobile AR advertising systems.

2. Materials and Methods

2.1 AR prototype system

To evaluate the proposed model, we developed a mobile AR advertising prototype system that operates on Android smartphones with AR capabilities. The system was designed as an integrated application rather than a static advertising interface, enabling real-time interaction and sensing-driven feedback. It consists of five core modules: (1) scene recognition and plane detection, (2) 3D advertising content loading, (3) interaction control, (4) layered information display, and (5) operation logging. The sensing hardware used in the proposed AR prototype system mainly consisted of smartphone-integrated camera and motion-sensing modules. The visual sensing component employed a rear RGB camera equipped with a complementary metal–oxide–semiconductor (CMOS) image sensor for continuous environmental image acquisition. The captured image frames were used for feature-point extraction, scene recognition, plane detection, and spatial mapping. In addition, the motion-sensing component utilized an embedded IMU, including a three-axis accelerometer and a three-axis gyroscope, to collect acceleration, orientation, and rotational-motion signals during user movement and interaction. The acquired visual and inertial sensing data were processed through the ARCore visual–inertial tracking framework to estimate device pose, maintain spatial registration, and stabilize virtual object placement within the real environment. Furthermore, the smartphone touch screen functioned as an interaction-sensing interface, enabling gesture-based operations such as dragging, scaling, and object rotation for real-time AR interaction control. Through this system, users can place virtual products within a real environment, inspect them from multiple viewpoints, manipulate them using touch-based gestures, and access product information via interactive hotspots. This design enables the simultaneous evaluation of both 3D presentation and interaction qualities within a realistic AR usage context. In addition, the conceptual framework of the proposed study is illustrated in Fig. 1, which presents the structural relationships among system-level antecedents, mediating variables, and behavioral outcomes. This model serves as the theoretical basis for system design and subsequent empirical validation.

2.2 Experimental scenario and task design

The experimental scenario was based on a consumer product suitable for 3D visualization and interactive exploration. In this study, the selected product category was consumer electronic merchandise, specifically a virtual smart wearable device used for mobile AR product visualization and interaction. This product type was chosen because it contains multiple visual and structural features suitable for 3D presentation, including curved surfaces, interface details,

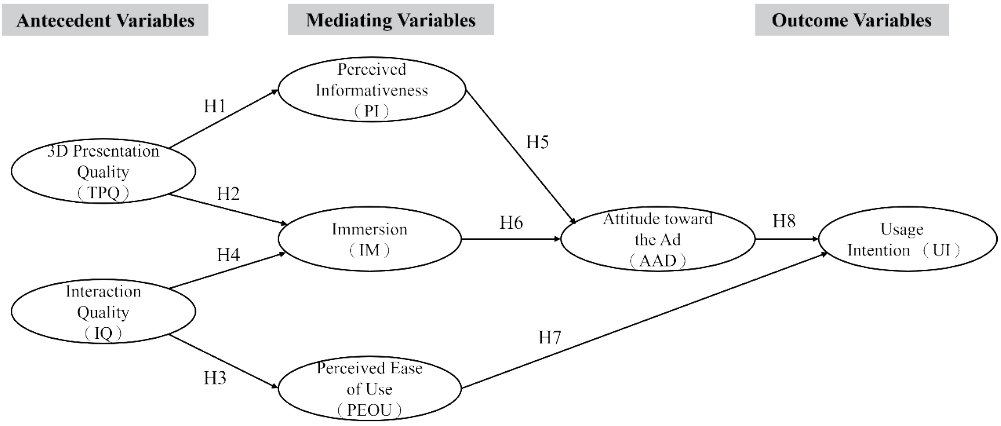

Fig. 1. Conceptual research model.

and interactive functional components. Participants can inspect the virtual product from different viewing angles, enlarge or rotate the object, and activate embedded information hotspots to obtain additional product specifications and usage-related information. The selected product scenario therefore provided an appropriate experimental context for evaluating sensing-enabled spatial presentation, interaction responsiveness, and user perception within the AR advertising environment. Participants were instructed to complete a standardized sequence of tasks, including scene scanning, virtual object placement, product inspection, rotation and scaling, viewpoint switching, and the activation of information hotspots. This structured task flow was designed to replicate a realistic mobile AR advertising experience while ensuring procedural consistency across participants. From a sensing perspective, these tasks engage key system functions such as spatial tracking, gesture recognition, and real-time rendering, allowing us to capture user responses under controlled yet representative conditions. During the experiment, the RGB camera continuously captured environmental image data, while the accelerometer and gyroscope simultaneously recorded motion and orientation signals generated during smartphone operation. These sensing data were dynamically integrated to support real-time spatial tracking, viewpoint estimation, and virtual-object alignment within the 3D AR scene. The obtained sensing information was further translated into interactive visual feedback through the rendering engine, allowing users to observe stable object placement and responsive viewpoint updating during AR interaction. To minimize environmental variability affecting AR performance, the experiment was conducted in an indoor setting with stable lighting conditions and a flat surface to ensure reliable plane detection and tracking stability. As shown in Fig. 2, the experimental setup supports consistent interaction conditions and the accurate evaluation of system performance.

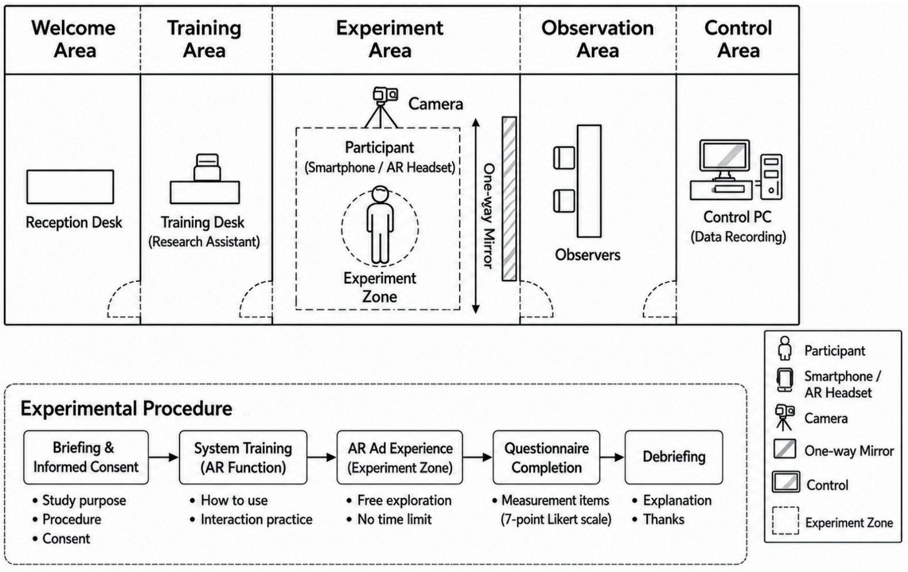

Fig. 2. AR prototype system/experimental setup.

2.3 Participants and procedure

Participants were recruited through a combination of convenience and purposive sampling, targeting individuals with general smartphone usage experience. Prior experience with AR systems was not required, as we aimed to capture responses representative of general users. Upon arrival, participants were briefed on the study objectives and procedures. Before the formal experiment, all participants received a brief operational training session to familiarize themselves with the AR interface and interaction procedures. The training mainly included smartphone handling, scene-scanning procedures, virtual object placement, touch-based rotation and scaling operations, and the activation of information hotspots within the AR environment. Participants were also instructed on how to maintain appropriate viewing distance and movement speed to ensure stable spatial tracking during interaction. The training session was conducted individually and required approximately 5–10 min per participant, depending on prior AR experience and operational familiarity. They then interacted with the AR advertising system following the predefined task sequence and completed the questionnaire immediately after the experience. A total of 350 participants completed the formal experiment and questionnaire survey. After data screening for incomplete or invalid questionnaires, valid responses from all 350 participants were retained for subsequent analysis.

2.4 Measures

The questionnaire included seven constructs: 3D presentation quality, interaction quality, perceived informativeness, immersion, perceived ease of use, attitude toward the advertisement, and usage intention. A total of 28 items were measured using a seven-point Likert scale ranging from 1 (strongly disagree) to 7 (strongly agree). All measurement items were adapted from established literature and refined to fit the mobile AR advertising context. Prior to the formal survey, expert review and pilot testing were conducted to ensure clarity, relevance, and content validity. Table 1 shows the constructs, operational definitions, sample items, and corresponding literature sources.

2.5 Data analysis

The data analysis was conducted in four stages. First, descriptive statistics were used to summarize the sample characteristics and variable distributions. Second, internal consistency reliability was evaluated during the pilot stage. Third, confirmatory factor analysis (CFA) was performed to assess the measurement model, including reliability, convergent validity, discriminant validity, and model fit. In the measurement evaluation process, McDonald's ω and Cronbach's α were used to assess internal consistency reliability, indicating the degree to which the measurement items consistently reflect the same latent construct. In addition, the Heterotrait–Monotrait (HTMT) ratio was employed to evaluate discriminant validity, indicating whether different constructs are empirically distinguishable from each other. Finally, structural

Table 1
Constructs, operational definitions, sample items, and corresponding literature sources.

Construct	Code	Operational definition	No. of items	Sample item	Main source(s)
3D presentation quality	TPQ	Extent to which the AR advertisement presents virtual objects in a visually clear, realistic, and spatially appropriate manner within the real environment	4	The 3D objects in this AR advertisement are naturally integrated into the real scene.	Prior mobile AR, visualization, and user experience studies
Interaction quality	IQ	Extent to which the AR advertisement provides intuitive, fluent, and responsive interaction during user operation	4	I can intuitively operate the functions in this AR advertisement.	Prior AR interaction and interface usability studies
Perceived informativeness	PI	Extent to which the AR advertisement provides useful, understandable, and decision-supportive product information	4	This AR advertisement provides useful product information.	Prior advertising informativeness and AR commerce studies
Immersion	IM	Degree to which users feel engaged, absorbed, and psychologically involved in the AR advertising experience	4	When using this AR advertisement, I feel immersed in the experience.	Prior immersion and AR experience studies
Perceived ease of use	PEOU	Extent to which users perceive the AR advertisement as easy to learn, easy to understand, and effortless to use	4	I think it is easy to learn how to use this AR advertisement.	Technology acceptance and usability studies
Attitude toward advertisement	AAD	Users' overall positive or negative evaluative response to the AR advertisement format and experience	4	I like this form of AR advertising.	Advertising attitude studies
Usage intention	UI	Extent to which users intend to reuse, continue using, or recommend this type of AR advertisement in the future	4	If I have the opportunity, I would use this type of AR advertisement again in the future.	Behavioral intention and AR adoption studies

Note: All items were measured using a seven-point Likert scale ranging from 1 = strongly disagree to 7 = strongly agree.

equation modeling (SEM) was conducted to test the hypothesized relationships and mediation effects among the constructs.

3. Results and Discussion

3.1 Sample characteristics

The final dataset comprised 350 valid responses, with no missing values observed in the demographic variables, ensuring data completeness for subsequent statistical analysis. The sample included both male and female participants, with a slightly higher proportion of female respondents, indicating a balanced gender distribution suitable for behavioral evaluation. The age distribution was concentrated between 21 and 40 years, representing the primary user group of smartphone-based applications. From a sensing and system interaction perspective, this demographic is particularly relevant, as it reflects users who are familiar with mobile interfaces and capable of engaging with sensor-driven interactive environments. Regarding technology usage behavior, most participants reported moderate to high levels of smartphone usage, suggesting sufficient familiarity with touch-based interaction and mobile system responsiveness. Furthermore, more than half of the participants had prior exposure to AR-related applications, such as AR advertising or product visualization systems.

This prior experience implies a baseline level of user understanding of sensor-mediated interactions, including camera-based tracking, spatial alignment, and gesture-based control. From a measurement perspective, the composition of the sample enhances the reliability of evaluating perception and interaction quality in mobile AR environments, as participants have the necessary experiential background to assess system performance. Overall, the sample characteristics support the validity of the experimental results and ensure that the findings are representative of typical mobile AR users. Table 2 shows the demographic attributes and usage-related characteristics of the participants, providing a descriptive foundation for subsequent measurement and structural analyses.

3.2 Reliability, descriptive statistics, and correlations

The pilot test demonstrated satisfactory internal consistency, with both McDonald's ω and Cronbach's α reaching 0.912 for the overall measurement scale, indicating a high level of reliability in capturing sensor-mediated user perceptions. This result confirms that the

Table 2
Sample characteristics of formal survey participants.

Variable	Category	*n*	%
Gender	Male	152	43.429
	Female	188	53.714
	Other	6	1.714
	Prefer not to say	4	1.143
Age	Under 20	30	8.571
	21–30	165	47.143
	31–40	98	28.000
	41–50	37	10.571
	51 and above	20	5.714
Current status	Student	8	2.286
	Office worker	52	14.857
	Freelancer	149	42.571
	Researcher/Teacher	109	31.143
	Other	32	9.143
Smartphone use frequency	Rarely	8	2.286
	Occasionally	79	22.571
	Moderate	130	37.143
	Frequently	113	32.286
	Very frequently	20	5.714
AR use experience	Never	89	25.429
	Occasionally	137	39.143
	Several times	89	25.429
	Frequently	35	10.000
Prior exposure to AR advertising	No	143	40.857
	Yes	207	59.143

Note: Valid sample size = 350; no missing values were found in the demographic items.

measurement items consistently reflect the underlying constructs associated with 3D presentation and interaction quality in mobile AR environments. In the formal survey, the mean values of the observed variables were generally distributed in the mid-to-upper range of the response scale, suggesting that participants exhibited overall positive evaluations of the mobile AR advertising system. From a system performance perspective, this trend implies that the sensing-driven processes, such as visual rendering, spatial alignment, and interaction responsiveness, were perceived as functionally effective by users.

Among the seven constructs, perceived ease of use exhibited the highest mean score, indicating that the interaction mechanisms supported by the sensing system were generally intuitive and easy to operate. This was followed by 3D presentation quality and perceived informativeness, suggesting that the system was effective in transforming sensor-acquired environmental data into a visually coherent and informative content. In contrast, immersion and usage intention showed relatively lower mean values, which may reflect limitations in sustained engagement or the depth of experiential integration within the current system configuration. Correlation analysis revealed that all constructs were positively and significantly associated with each other, with correlation patterns consistent with the proposed structural relationships. From a measurement perspective, these results provide preliminary empirical support for the coherence of the conceptual framework, indicating that sensing-derived presentation and interaction qualities are systematically linked to cognitive, affective, and behavioral responses. Table 3 shows the reliability coefficients, descriptive statistics, and interconstruct correlations, providing a quantitative foundation for subsequent CFA and structural model evaluation.

3.3 Measurement model

The CFA results indicate that the measurement model achieved a satisfactory overall fit, supporting the adequacy of the proposed factor structure. All seven constructs were empirically validated, demonstrating that the measurement framework reliably captures user perceptions associated with sensor-enabled 3D presentation and interaction processes in the mobile AR system. From a reliability perspective, all constructs exhibited strong internal consistency, with

Table 3
Reliability, descriptive statistics, and correlations of study constructs.

Construct	No. of items	McDonald's ω	Cronbach's α	Mean	1	2	3	4	5	6	7
1. TPQ	4	0.838	0.836	5.181	—						
2. IQ	4	0.800	0.800	5.056	0.671	—					
3. PI	4	0.850	0.851	5.149	0.626	0.640	—				
4. IM	4	0.893	0.893	4.899	0.400	0.434	0.543	—			
5. PEOU	4	0.869	0.868	5.263	0.684	0.660	0.663	0.412	—		
6. AAD	4	0.859	0.859	5.054	0.381	0.488	0.577	0.619	0.415	—	
7. UI	4	0.899	0.898	4.852	0.437	0.456	0.561	0.413	0.465	0.497	—

Note: TPQ = 3D presentation quality, IQ = interaction quality, PI = perceived informativeness, IM = immersion, PEOU = perceived ease of use, AAD = attitude toward the advertisement, and UI = usage intention. McDonald's ω and Cronbach's α represent internal consistency reliability indices, indicating the consistency of the measurement items within each construct. Off-diagonal values are Pearson's correlation coefficients.

composite reliability and Cronbach's α values exceeding the commonly accepted thresholds. This confirms that the measurement items consistently represent the latent constructs derived from sensing-driven system attributes. In terms of convergent validity, the average variance extracted (AVE) values for all constructs were above the recommended level, indicating that each construct explains a substantial proportion of variance in its corresponding indicators.

Discriminant validity was further examined using the HTMT, and all values remained below the recommended cutoff, confirming that the constructs are empirically distinct. This distinction is particularly important in this study, as 3D presentation and interaction qualities originate from different sensing and processing mechanisms, namely, visual rendering and spatial registration versus interaction responsiveness and sensor feedback. From a measurement and system perspective, these results demonstrate that the proposed model provides a stable and well-separated representation of sensing-mediated perceptual constructs. This ensures that subsequent structural analysis can reliably interpret the transformation from sensor-derived stimuli to cognitive, affective, and behavioral responses. Table 4 shows the detailed results of the measurement model evaluation, including reliability indices, convergent validity, discriminant validity, and overall model assessment.

3.4 Structural model and mediation effects

The SEM results indicate that the proposed model achieved a satisfactory overall fit, supporting the adequacy of the hypothesized relationships among sensing-derived system attributes, perceptual constructs, and behavioral outcomes. In terms of direct effects, 3D presentation quality exhibited a significant positive effect on perceived informativeness, indicating that improvements in rendering fidelity, spatial alignment, and visual clarity effectively enhance users' ability to extract meaningful information from the AR environment. However, its direct effect on immersion was not statistically significant, suggesting that visual realism alone may be insufficient to induce a deeper experiential state without complementary interaction support. Similarly, interaction quality showed a significant positive effect on

Table 4
Measurement model results.

Construct	No. of items	McDonald's ω	Cronbach's α	AVE	Maximum HTMT involving the construct	Assessment
TPQ	4	0.838	0.836	0.563	0.818	Good
IQ	4	0.800	0.800	0.501	0.818	Acceptable
PI	4	0.850	0.851	0.590	0.773	Good
IM	4	0.893	0.893	0.677	0.701	Good
PEOU	4	0.869	0.868	0.625	0.803	Good
AAD	4	0.859	0.859	0.605	0.701	Good
UI	4	0.899	0.898	0.691	0.638	Good
Overall scale	28	0.967	0.947	—	—	Good

Note-measurement model fit indices: $\chi^2 = 327.700$, $df = 329$, $p = .510$, $\chi^2/df = 0.996$, $CFI = 1.000$, $TLI = 1.000$, $NNFI = 1.000$, $NFI = 0.945$, $PNFI = 0.823$, $RFI = 0.937$, $IFI = 1.000$, $RNI = 1.000$, $GFI = 0.939$, $RMSEA = 0.000$, $RMSEA$ 90% CI = 0.000–0.020, and $SRMR = 0.027$. All HTMT values were below the recommended threshold.

perceived ease of use, reflecting that sensing responsiveness, gesture recognition accuracy, and system feedback mechanisms play a critical role in facilitating intuitive operation. In contrast, its direct effect on immersion was also not significant, implying that interaction efficiency primarily contributes to usability rather than directly to immersive experience formation. Further analysis revealed that perceived informativeness and immersion both had significant positive effects on attitude toward the advertisement, indicating that cognitive clarity and experiential engagement jointly shape evaluative responses.

In addition, perceived ease of use and attitude significantly enhanced usage intention, demonstrating that both operational simplicity and favorable evaluation are key determinants of behavioral intention in sensor-enabled AR systems. From a mediation perspective, the results highlight a multi-stage transformation mechanism linking sensing-driven system performance to behavioral outcomes. Specifically, 3D presentation quality indirectly affected attitude through perceived informativeness, while interaction quality indirectly affected usage intention through perceived ease of use. Furthermore, perceived informativeness and immersion both exerted indirect effects on usage intention through attitude, confirming its role as a central integrative construct. Overall, six of the eight hypotheses were supported. From a system-level perspective, these findings suggest that sensing-derived visual presentation and interaction processes do not directly translate into behavioral outcomes; rather, their effects are mediated through cognitive and affective evaluations. This highlights the importance of optimizing not only sensing accuracy and interaction responsiveness but also the interpretability and experiential quality of system outputs. Table 5 presents the structural model fit indices and standardized path coefficients for Hypotheses 1–8, while Table 6 shows the indirect effects and mediation analysis results.

4. Discussion

4.1 Main findings

In this study, we provide empirical evidence that the proposed mobile AR advertising system was generally evaluated positively by users, particularly in terms of perceived ease of use, 3D presentation quality, and perceived informativeness. These findings suggest that the developed AR system was effective in supporting core functional requirements, including stable visual presentation, understandable information delivery, and intuitive user operation. From a sensing and system-performance perspective, the results indicate that the integration of smartphone-based visual sensing, spatial registration, and touch-responsive interaction successfully generated a usable and cognitively accessible advertising environment. At the same time, immersion and usage intention were relatively lower than the more function-oriented evaluations. This pattern indicates that users more readily recognized the practical utility of the system than its ability to produce a deeply engaging experiential state.

In other words, the current AR configuration appears to have performed more strongly as a sensor-enabled information and interaction platform than as a fully immersive experiential medium. This distinction is important because it shows that acceptable system usability and information clarity do not automatically translate into stronger affective engagement or a higher

Table 5
Structural model fit and direct path estimates.
Panel A: structural model fit

Fit index	Criterion	Result	Assessment
χ^2	—	439.831	—
df	—	341	—
p	> .05	< .001	Acceptable
χ^2/df	< 3.00	1.290	Good
CFI	> 0.90	0.982	Good
TLI	> 0.90	0.981	Good
NNFI	> 0.90	0.981	Good
NFI	> 0.90	0.927	Good
PNFI	> 0.50	0.836	Good
RFI	> 0.90	0.919	Good
IFI	> 0.90	0.983	Good
RNI	> 0.90	0.982	Good
GFI	> 0.90	0.919	Good
RMSEA	< 0.08	0.029	Good
RMSEA 90% *CI*	—	0.020–0.036	Good
SRMR	< 0.08	0.049	Good

Panel B: direct path estimates

Hypothesis	Path	Standardized coefficient (β)	z-value	p-value	Result
H1	TPQ → PI	0.825	35.385	< .001	Supported
H2	TPQ → IM	0.267	1.097	.272	Not supported
H3	IQ → PEOU	0.864	38.595	< .001	Supported
H4	IQ → IM	0.290	1.187	.235	Not supported
H5	PI → AAD	0.376	7.996	< .001	Supported
H6	IM → AAD	0.517	12.908	< .001	Supported
H7	PEOU → UI	0.341	5.831	< .001	Supported
H8	AAD → UI	0.409	7.057	< .001	Supported

Note: The explained variance values were $R^2 = 0.581$ for AAD and $R^2 = 0.420$ for UI.

Table 6
Indirect effects and mediation results.

Indirect path	Indirect effect	*SE*	z-value	p-value	95% *CI*	Result
TPQ → PI → AAD	0.311	0.041	7.585	< .001	0.231–0.390	Supported
TPQ → IM → AAD	0.138	0.125	1.104	.270	—	Not supported
IQ → IM → AAD	0.150	0.129	1.166	.244	—	Not supported
IQ → PEOU → UI	0.294	0.052	5.633	< .001	—	Supported
PI → AAD → UI	0.154	0.031	4.948	< .001	0.093–0.215	Supported
IM → AAD → UI	0.211	0.034	6.206	< .001	—	Supported

Note: The indirect effects above summarize the mediation pathways in the structural model. When exporting the complete defined parameters / indirect effects table from Jeffreys's Amazing Statistics Program, replace the dashes in the *CI* column with the corresponding confidence intervals reported by the software.

intention to continue using AR advertising. From a broader interpretation, the results imply that mobile AR advertising may initially be accepted by users through functional value rather than experiential novelty alone. This is consistent with the current stage of many consumer AR applications, in which users tend to value ease of operation and informative product visualization before forming deeper emotional attachment or repeated-use intentions. Therefore, the findings highlight that, in sensor-enabled advertising systems, usability and information representation remain foundational conditions for user acceptance, whereas immersion may require additional experiential design elements beyond basic visual overlay and interaction support.

4.2 Distinct roles of 3D presentation and interaction qualities

One of the most important findings of this study is that 3D presentation and interaction qualities played distinct roles in the formation of user responses. Although both are essential components of a mobile AR advertising system, they affected different perceptual pathways and should not be treated as interchangeable design dimensions. 3D presentation quality primarily exerted its effect through perceived informativeness. This finding suggests that when virtual content is visually clear, spatially aligned with the real environment, and presented with sufficient 3D fidelity, users are better able to interpret product characteristics and extract useful information from the AR display. From a sensing perspective, this result reflects the importance of stable environmental recognition, accurate plane detection, and reliable rendering alignment. More specifically, the environmental image signals captured by the camera sensor were transformed into spatial feature-point representations, while the accelerometer and gyroscope signals provided continuous motion and orientation estimation. Through sensor fusion and coordinate mapping processes, these signals were converted into a stable 3D reference space for virtual object placement and visualization. Therefore, users' evaluations of 3D presentation quality were not only associated with graphical appearance, but also strongly related to the sensing accuracy and spatial consistency of the underlying AR tracking system.

If these underlying sensing and rendering processes are well executed, users perceive the AR content not merely as visually attractive, but as informative and meaningful. Thus, the value of 3D presentation lies in not only visual novelty, but also its ability to organize and communicate product information more effectively than conventional flat advertising formats. In contrast, interaction quality mainly operated through perceived ease of use. This indicates that responsive system behavior, intuitive control logic, and smooth feedback mechanisms reduce the operational burden placed on users and improve their usability judgments. Unlike 3D presentation quality, which is more closely linked to visual comprehension, interaction quality reflects the extent to which the AR system supports efficient and low-friction user action. This distinction is particularly relevant in sensor-enabled systems, because interaction quality depends heavily on the responsiveness of the sensing-feedback loop, including input recognition, gesture execution, and display update latency. When this loop functions smoothly, users are more likely to consider the system easy to use, even if the immersive effect remains limited. The nonsignificant direct effects of both 3D presentation and interaction qualities on immersion also deserve attention.

This result suggests that immersion in mobile AR advertising is not determined solely by higher display quality or smoother operation. Instead, immersion may require a more integrated experiential condition, involving narrative coherence, contextual relevance, emotional resonance, or richer multisensory engagement. In practical terms, a system can be visually accurate and operationally efficient without necessarily creating a strong sense of psychological absorption. This helps explain why the current AR prototype was effective in supporting informative and usable interaction, but less effective in directly stimulating immersion. Taken together, these findings indicate that 3D presentation and interaction qualities represent two related but functionally different subsystems within mobile AR advertising. The former contributes primarily to informational interpretation, whereas the latter supports operational fluency.

Recognizing this distinction is important for both theory and design. This distinction also represents an important contribution of this study compared with prior AR-related research. Many existing studies evaluate AR experience as a unified perceptual construct and primarily focus on general usability, entertainment, or purchase intention outcomes. In contrast, we demonstrate that sensing-driven visual presentation and interaction responsiveness function through different perceptual pathways and contribute to different stages of user evaluation. By separately modeling these two dimensions, the proposed framework provides a more detailed interpretation of how sensing-system performance is transformed into cognitive and behavioral responses. This measurement-oriented perspective extends beyond traditional marketing-oriented AR studies and offers a clearer connection between sensing mechanisms and user perception. This is because it clarifies that improvements in visual presentation and interaction responsiveness may enhance different aspects of user experience rather than producing identical downstream effects, thereby indicating that each design factor contributes to user perception, engagement, and behavioral intention through distinct psychological and experiential mechanisms.

4.3 Theoretical and design implications (condensed)

The findings provide important implications for mobile AR advertising and sensor-enabled interactive systems. The novelty of this study lies in its integration of sensing-oriented system attributes with behavioral evaluation in mobile AR advertising. Unlike conventional AR advertising studies that primarily emphasize user attitude or marketing effectiveness, in the present work, we separately analyze 3D presentation and interaction qualities as two sensing-derived system dimensions and examine their distinct perceptual pathways through SEM analysis. By linking spatial sensing, interaction responsiveness, perceptual cognition, and behavioral intention within a unified measurement framework, we provide a more engineering-oriented interpretation of AR user experience and contribute a sensor-enabled evaluation perspective for future immersive interactive systems. First, the results support a staged mechanism in which system-level attributes affect behavioral intention indirectly through cognitive and affective processes. 3D presentation quality enhances perceived informativeness, interaction quality improves perceived ease of use, and both contribute to attitude, which subsequently drives usage intention. This confirms that sensing-derived system outputs must be interpreted by users before affecting behavior. From a measurement perspective, we demonstrate how sensing functions—such as spatial alignment, rendering, and interaction feedback—are translated into perceptual evaluations.

The effectiveness of AR systems therefore depends on not only technical implementation but also how clearly and responsively sensor-generated outputs are perceived by users. In particular, we indicate that the sensing quality of RGB camera modules, CMOS image acquisition systems, inertial sensing devices, and touch-responsive interaction interfaces may directly affect users' evaluations of spatial stability, interaction fluency, and perceived informativeness in AR environments. This finding suggests that future improvements in image-sensing accuracy, motion-tracking precision, and low-latency sensor-fusion mechanisms can further enhance the perceptual quality and usability of mobile AR advertising systems. From a sensor-engineering perspective, the findings also provide practical guidance for future sensing-device and sensing-material development. The significant effect of interaction responsiveness and spatial presentation quality suggests that future AR systems may benefit from higher-sensitivity motion sensors, lower-latency inertial sensing modules, and more stable vision-based tracking technologies. In addition, the results imply that sensor-integrated display materials and lightweight multimodal sensing architectures capable of improving spatial consistency and real-time feedback may further enhance user perception and immersive interaction quality. Therefore, the proposed framework can serve as not only a behavioral evaluation model, but also a reference for optimizing sensing performance and sensor-supported AR system design. Second, attitude toward the advertisement acts as a key integrative construct, linking functional evaluation and experiential response to behavioral intention.

In addition, immersion plays an important role in shaping attitude, although it is not directly determined by presentation or interaction quality. This suggests that immersive experience depends on broader design factors beyond core system performance. From a design perspective, several priorities emerge. Accurate 3D display is essential for improving perceived informativeness, requiring reliable spatial tracking and visual consistency. Smooth interaction flow is critical for enhancing perceived ease of use, highlighting the importance of low-latency sensing and responsive feedback. Clear and structured information presentation further supports user understanding, while additional experiential design elements, such as contextual or emotionally engaging content, are needed to strengthen immersion. Overall, the results indicate that effective mobile AR advertising should be developed as an integrated sensor-enabled system in which sensing, rendering, interaction, and content design are jointly optimized to support both functional evaluation and experiential response.

4.4 Limitations and future research

Several limitations should be acknowledged. First, although the sample included participants with different demographic and usage backgrounds, it was still dominated by relatively young users with substantial smartphone experience. As a result, the findings may primarily reflect digitally familiar user groups rather than older or less experienced populations. Since usability perception and interaction tolerance may vary across users, future studies should include more diverse age ranges and technology-experience profiles to improve generalizability. Second, the experiment was based on a single product scenario. While this ensured procedural consistency, it may limit applicability to other advertising categories. Different products may require distinct forms of AR presentation and interaction. Future research should therefore validate the model across multiple product types and application contexts to examine its robustness under varying conditions. Third, we employed a cross-sectional self-report design, which may not fully capture actual behavior during AR interaction. Self-reported intention does not always correspond to real usage patterns. Future studies should incorporate objective sensing data, such as operation logs, dwell time, or interaction trajectories, to better align subjective evaluation with observed behavior and improve ecological validity.

Fourth, the current model focused on perceptual constructs but did not explicitly include engineering-level system metrics, such as tracking accuracy, registration error, and response latency. Integrating these sensing-related indicators with perceptual measures would provide a more comprehensive evaluation framework linking system performance and user experience. Finally, the nonsignificant direct effects on immersion suggest that additional antecedents should be considered. In addition, ethical concerns related to mobile AR advertising should also be considered in future research. Because AR systems can generate highly realistic and spatially integrated virtual content, there is a potential risk that consumers may misinterpret virtual representations as actual product characteristics or overestimate product functionality due to immersive presentation effects. From a consumer-protection perspective, future sensor-enabled AR advertising systems should therefore emphasize transparent information representation, accurate spatial visualization, and responsible interaction design to reduce the possibility of misleading or manipulative advertising practices. Further studies may also examine how sensing accuracy, information disclosure mechanisms, and user-awareness indicators affect consumer trust and ethical acceptance in immersive advertising environments. Factors such as narrative design, emotional engagement, contextual relevance, and multimodal interaction may further contribute to immersive experience formation and should be explored in future work. In summary, although we provide a validated framework for understanding the effects of 3D presentation and interaction quality, further research is needed to extend the model across broader user groups, product scenarios, and measurement approaches, thereby strengthening its contribution to sensor-enabled AR system evaluation.

5. Conclusions

In this study, we developed and empirically validated a sensor-enabled 3D presentation and interaction model for mobile AR advertising. The results demonstrated that the proposed measurement framework achieved satisfactory reliability, validity, and overall structural fit, confirming its suitability for evaluating user responses in sensor-mediated AR environments. The findings revealed that 3D presentation quality primarily enhanced perceived informativeness, while interaction quality mainly improved perceived ease of use. Furthermore, both cognitive and affective mechanisms contributed to attitude formation, which subsequently affected usage intention. These results highlight a multi-stage transformation process in which sensing-driven system attributes are interpreted by users and translated into behavioral outcomes. From a sensing perspective, we show that the effectiveness of mobile AR advertising depends on not only technical deployment, but also how sensor-generated visual and interactive outputs are perceived and evaluated by users. The proposed model provides a structured framework linking sensing mechanisms, perceptual processing, and behavioral intention, thereby extending the application of measurement approaches in sensor-enabled interactive systems. In addition to its behavioral and measurement contributions, we also provide potential directions for future sensor and sensing-material research in AR applications. The identified relationships among sensing responsiveness, spatial stability, and user perception indicate that improvements in motion sensing accuracy, environmental recognition capability, sensor-fusion efficiency, and low-latency interactive materials may directly affect the user acceptance of AR systems. Consequently, the proposed framework may support the future development of sensor-integrated mobile platforms, multimodal sensing architectures, and responsive display technologies for next-generation immersive interactive environments. Overall, mobile AR advertising should be understood as an integrated sensor-supported system, where presentation quality, interaction responsiveness, and user perception must be jointly optimized. Future design should therefore emphasize accurate spatial representation, low-latency interaction, and clear information delivery to enhance both functional usability and experiential effectiveness.

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