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PAPER

Application of Mobile Augmented Reality Interaction in Visual Communication Design Education

Ruiyi Li (✉)

Hebei Art & Design Academy, Baoding, China

m15028297959@163.com

ABSTRACT

Mobile augmented reality offers technical support for the advancement of visual communication design pedagogy, which is currently shifting toward three-dimensional spatial representation and dynamic interaction. Conventional instructional media exhibit inherent limitations in cultivating the core competencies required by this paradigm shift. Existing augmented reality teaching tools are predominantly technology-driven and inadequately aligned with authentic pedagogical needs, and their effectiveness assessments tend to emphasize affective dimensions while lacking systematic quantification of professional design competencies, thereby constraining large-scale adoption. This study proposes a design-thinking-driven development paradigm, operationalized through a five-stage closed-loop process that anchors technical implementation to competency development objectives. Leveraging Unity 3D integrated with Vuforia and ARCore, three core interactive modalities were implemented: three-dimensional preview, hierarchical information visualization, and interactive narrative feedback. A dual-layer quantitative evaluation model was established, comprising a professionally validated competency assessment scale, to verify efficacy from both user experience and competence gain dimensions. Five comparative and ablation experiments demonstrated good usability of the tool and significant improvement in students' core competencies, including spatial form generation and dynamic visual expression, with the methodological framework exhibiting cross-course reusability. This study contributes a complete "development-validation" methodological system, providing a replicable paradigm and evidence-based assessment approach for the application of mobile augmented reality in design education.

KEYWORDS

mobile augmented reality, design thinking, visual communication design education, interaction design, competency assessment, educational technology

1 INTRODUCTION

With the sustained enhancement of mobile terminal computing performance and the widespread adoption of mobile augmented reality development

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frameworks such as ARCore and ARKit, mobile augmented reality technologies have progressively permeated educational settings beyond their initial applications in consumer entertainment [1, 2]. Compared with head-mounted augmented reality devices, mobile terminals offer advantages including high portability, low deployment costs, and broad scenario adaptability, thereby accommodating both classroom instruction and self-directed after-class learning and providing a feasible technological pathway for the scaled implementation of immersive learning experiences [3, 4]. Within the domain of visual communication design education, the iterative evolution of industry talent demands has driven pedagogical objectives to expand from conventional static graphic creation toward multidimensional competencies encompassing three-dimensional spatial expression, dynamic visual narration, and interactive logic design. Traditional instructional approaches, which rely on paper-based media and two-dimensional screen displays for content presentation, are inherently inadequate for directly conveying spatial depth relationships, dynamic motion trajectories, and interactive feedback mechanisms. Consequently, cognitive barriers persist in the cultivation of core competencies such as spatial form perception, dynamic rhythm control, and interactive logic construction [5, 6]. The deep integration of mobile augmented reality technologies into design education represents a critical direction for addressing current pedagogical bottlenecks and aligning with industry talent development needs. The establishment of a systematic development and validation methodology constitutes a prerequisite for ensuring the effectiveness of technological applications and avoiding technology-driven biases [7, 8].

Three prominent limitations remain evident in current research on mobile augmented reality applications in education. Regarding the logic of tool development, most studies are driven primarily by technological implementation, with direct reuse of generic augmented reality functional modules, and the development process lacks a systematic mapping mechanism between technical functionalities and disciplinary teaching objectives. This results in a misalignment between tool functionalities and the competency development needs of authentic instructional settings, characterized by the coexistence of technical redundancy and deficiencies in core pedagogical requirements [9, 10]. With respect to the efficacy evaluation framework, existing studies predominantly concentrate validation efforts on affective and attitudinal dimensions, including learning motivation, classroom engagement, learning interest, and satisfaction, whereas a structured and quantitative measurement system targeting the core competencies of design disciplines has yet to be established. Consequently, the pathways and effect sizes through which augmented reality technologies influence the development of capabilities such as spatial expression, dynamic narration, and interaction design remain insufficiently clarified, thereby limiting the instructional guidance value of research findings [11, 12]. In terms of methodological frameworks, current contributions largely consist of application cases confined to single courses or localized instructional activities, with insufficient continuity among tool requirement analysis, functional development, pedagogical implementation, and efficacy validation. A closed-loop research paradigm spanning from needs elicitation and tool development to efficacy validation has not yet materialized [13, 14]. The reproducibility of research procedures, reusability of tool resources, and cross-course transferability of findings remain inadequate, constraining the large-scale dissemination and standardized construction of mobile augmented reality pedagogical applications [15].

To address the aforementioned research gaps, a design-thinking-driven development paradigm for mobile augmented reality teaching tools is proposed, whereby the native methodologies of design disciplines are incorporated into the full-lifecycle development of educational tools. Through a five-stage closed-loop process, the alignment of tool functionalities with professional competency development requirements is ensured. A dual-layer quantitative efficacy evaluation model is constructed, and a competency assessment scale tailored to visual communication design is developed, enabling precise two-dimensional measurement encompassing both user experience quality and professional competence gains. Three core interaction modalities are implemented based on the Unity 3D, Vuforia, and ARCore technology stack, thereby constituting a complete integrated methodological framework for development and validation. Through multiple controlled and ablation experiments, the mechanisms through which interactive features influence competency enhancement are elucidated, providing replicable methodological support for the application of mobile augmented reality in design education.

The remainder of this work is organized into four sections. The second section systematically elaborates on the design-thinking-driven development workflow, the technical implementation details of the mobile augmented reality system, and the construction logic of the dual-layer quantitative evaluation model. The third section presents the experimental design, along with the implementation procedures and result analyses of the five groups of experiments. The fourth section summarizes the core conclusions and provides an outlook on future research directions.

2 RESEARCH METHODOLOGY AND SYSTEM IMPLEMENTATION

2.1 Integrated “development–validation” methodological framework

An integrated methodological framework for development and validation is established in this study, whereby the full-cycle development of mobile augmented reality teaching tools and multidimensional efficacy evaluation are consolidated into a coherent research pipeline. Figure 1 illustrates the architecture of the design-thinking-driven integrated “development–validation” framework for mobile augmented reality teaching tools. The entire tool development process is guided by design thinking methodology, with functional boundaries and interaction modalities defined on the basis of authentic pedagogical needs and competency development objectives in visual communication design education, thereby fundamentally circumventing technology-driven development biases and ensuring precise alignment between tool functionalities and teaching goals. The efficacy validation phase employs a dual-layer quantitative evaluation model, through which systematic measurements are conducted across two dimensions—user experience quality and professional competence gains—so as to provide reproducible empirical evidence for the instructional effectiveness of the tool. The tool prototype generated during the development phase serves as the research vehicle for efficacy validation, while the quantitative data produced during the validation phase, in turn, inform iterative tool optimization. These two phases jointly constitute a logically coherent closed-loop system, offering a standardized methodological reference for the deployment of mobile augmented reality in design education contexts.

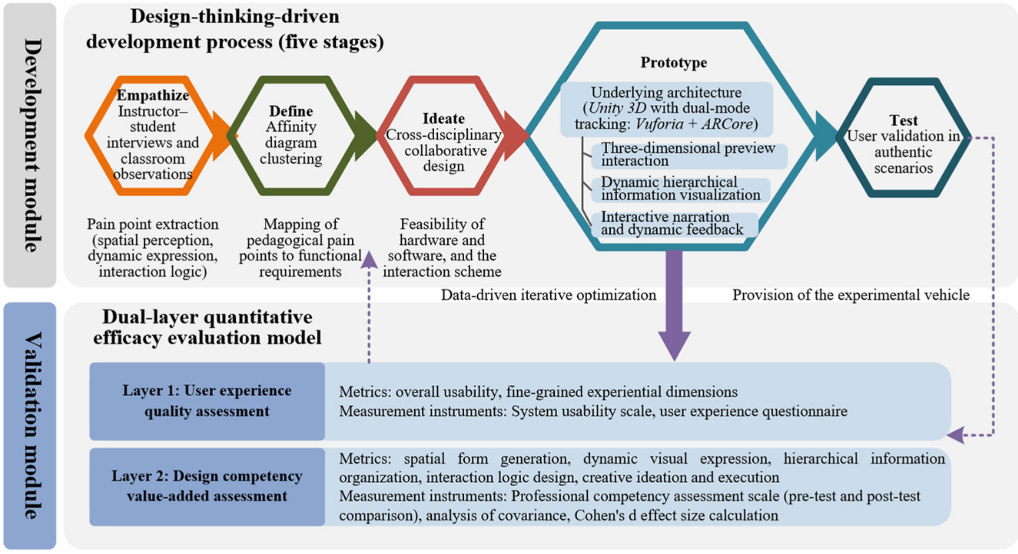

Fig. 1. Design-thinking-driven integrated "development–validation" framework for mobile augmented reality teaching tools

2.2 Design-thinking-driven development paradigm for mobile augmented reality teaching tools

The design thinking methodology was adapted to the full-cycle development of mobile augmented reality teaching tools, resulting in a five-stage closed-loop development pipeline comprising empathize, define, ideate, prototype, and test. During the empathize phase, semi-structured interviews and classroom observations were conducted with instructors and students from visual communication design programs, with a sample size of 15 to 20 participants. Learning pain points were extracted across three core competency dimensions—spatial form generation, dynamic visual expression, and interaction design—and interview data were coded and key requirement terms extracted through thematic analysis. In the define phase, requirement items were clustered via the affinity diagram method, establishing a direct mapping between pedagogical pain points and functional requirements, whereby qualitative research findings were translated into actionable interaction functional specifications. During the ideate phase, a cross-disciplinary collaborative design team was assembled, and interaction schemes along with feasibility assessment reports were produced within the technical constraints of mobile hardware performance, screen dimensions, and sensor precision. In the prototype phase, a biweekly agile development cycle was adopted, and runnable versions compatible with both major mobile operating systems were concurrently delivered. During the test phase, the prototype was embedded into authentic instructional settings for multiple rounds of user validation, with quantitative and qualitative feedback integrated to drive continuous iteration, culminating in a methodological closed loop tailored to design education tool development.

At the system foundation level, Unity 3D was employed as the rendering engine, with Vuforia and ARCore integrated to construct a dual-mode tracking architecture, thereby ensuring recognition accuracy and operational stability in mobile scenarios. Natural feature point extraction and matching were handled by the Vuforia module, with a feature point matching threshold set at 0.75, enabling rapid recognition and stable tracking of graphics, grids, and color blocks within graphic design works. Real-time device spatial pose estimation was performed by the ARCore module through concurrent odometry and mapping technology, with dynamic correction applied to virtual content drift induced by camera shake. The parallel operation of these two modules accommodated both target recognition flexibility and spatial positioning accuracy, adapting to varying lighting conditions and handheld operation scenarios in classroom environments and providing a stable technical foundation for higher-level interaction functionalities.

A mapping database linking planar visual elements to three-dimensional assets was established in the three-dimensional preview interaction module. Upon target image recognition, corresponding three-dimensional models were automatically loaded, and free viewpoint adjustment was enabled through a touch-gesture mapping algorithm. Single-finger swipe operations were mapped to Euler-angle rotations of the model, while two-finger pinch gestures corresponded to linear scaling transformations of the model matrix, allowing learners to observe the spatial morphology and structure of design objects from any angle, thereby compensating for the perceptual limitations of planar media in spatial comprehension. In the dynamic hierarchical information visualization interaction module, mapping rules for projecting planar information into three-dimensional depth were constructed, whereby text and graphic elements at different hierarchical levels were arranged along the spatial Z-axis at fixed proportional intervals. Horizontal swipe distances on the screen were linearly coupled to the depth position of the viewpoint, with depth-of-field blur effects employed to reinforce spatial hierarchy perception, facilitating learners' intuitive understanding of the hierarchical logic inherent in layout information.

The interactive narration and dynamic feedback module implemented click-and-drag responses for virtual objects through collision detection mechanisms, with a finite-state machine employed to govern the triggering and switching logic of dynamic feedback. Visual effects including color gradients and morphological deformations were rendered via procedural shaders, while Bézier curves were used to control element motion trajectories and rhythmic pacing, thereby establishing a direct association between operational behaviors and visual feedback and supporting learners in developing a coherent cognitive mapping between interaction logic and dynamic visual expression. All three interaction modalities were derived from and grounded in the translation of pedagogical requirements, establishing a one-to-one correspondence with design competency development objectives. These modalities not only embodied the interactive characteristics of mobile augmented reality technology but also ensured the instructional appropriateness of tool functionalities, providing a functionally complete research vehicle for subsequent efficacy validation.

2.3 Dual-layer quantitative efficacy evaluation model

Layer 1: user experience quality assessment. The first layer of assessment was focused on the user experience quality of the tool, with the system usability scale initially employed to conduct quantitative measurement of overall usability. This scale comprises 10 five-point Likert items, with odd-numbered items phrased positively and even-numbered items phrased negatively. The score was calculated using the following formula:

$$SUS = \left(\sum_{i=1}^{5} (X_{2i-1} - 1) + \sum_{i=1}^{5} (5 - X_{2i}) \right) \times 2.5 \tag{1}$$

where, X_j denotes the user rating for the j-th item, with values ranging from 1 to 5. During the calculation, baseline correction was performed for positively phrased items by subtracting 1, while directional correction for negatively phrased items was performed by taking the difference between 5 and the raw score. The sum of all corrected item scores was then multiplied by a factor of 2.5, normalizing the final score to a continuous interval from 0 to 100. In this study, a threshold of 68 was adopted as the criterion for acceptable usability and 70 as the criterion for good usability, through which the operational convenience and learning adaptability of the mobile augmented reality teaching tool in authentic classroom settings were examined, thereby excluding the systematic interference of tool usability bias on subsequent competency assessment outcomes.

To further decompose the user experience into fine-grained sub-dimensions, the user experience questionnaire was introduced to conduct multi-dimensional experiential assessment. This questionnaire establishes an evaluation framework across six dimensions—attractiveness, perspicuity, efficiency, dependability, stimulation, and novelty—enabling fine-grained characterization of the subjective perceptual experience of the tool. Among these, the perspicuity and efficiency dimensions correspond to the level of functional usability of the tool, the dependability dimension corresponds to users' subjective perception of technical stability, the attractiveness and novelty dimensions correspond to the motivational effects induced by technological novelty, and the stimulation dimension corresponds to the intensity of immersive experience during interaction. The combined use of the system usability scale and the user experience questionnaire simultaneously yields standardized overall usability scores and differentiated profiles across experiential sub-dimensions, thereby providing experience-level empirical data to inform iterative tool optimization while also establishing an experiential baseline for the second-layer professional competency value-added assessment, thus achieving layered decoupling of tool attributes from pedagogical efficacy.

Layer 2: design competency value-added assessment. The second layer of assessment was focused on the value-added measurement of core competencies in visual communication design, for which a professional competency assessment scale was constructed to enable systematic quantification across multiple competency dimensions. The scale encompasses five dimensions: spatial form generation, dynamic visual expression, hierarchical information organization, interaction logic design, and creative ideation and execution. For each dimension, four to five observable evaluation indicators were established, with a seven-point Likert scoring rule adopted. Student design assignments were independently graded in a blind review manner by three professional instructors holding associate professor or higher titles, and the mean score was taken as the final score for each dimension, thereby controlling for measurement bias arising from subjective evaluation. To quantify competency changes induced by pedagogical intervention, value-added scores were calculated using pre-test and post-test differences, with the following formula:

$$\Delta D_k = \bar{D}_{k,post} - \bar{D}_{k,pre} \tag{2}$$

where, ΔD_k denotes the value-added score for the k-th competency dimension, $\bar{D}_{k,post}$ denotes the post-test mean score for that dimension, and $\bar{D}_{k,pre}$ denotes the corresponding pre-test baseline score. A positive value-added score indicates an improvement in competency level, with larger magnitudes signifying more substantial competency gains attributable to the pedagogical intervention.

To exclude the confounding effect of initial competency baselines on intervention efficacy evaluation, between-group differences in value-added scores were tested using analysis of covariance, with pre-test scores entered as the covariate, instructional intervention modality as the fixed factor, and post-test scores compared across groups after baseline adjustment. To further quantify the practical magnitude of intervention effects, Cohen's d was adopted as the effect size indicator, calculated as follows:

$$d = \frac{\bar{D}_{exp} - \bar{D}_{ctrl}}{s_{pooled}} \tag{3}$$

where, the pooled standard deviation s_{pooled} was computed as:

$$s_{pooled} = \sqrt{\frac{(n_{exp} - 1)s_{exp}^2 + (n_{ctrl} - 1)s_{ctrl}^2}{n_{exp} + n_{ctrl} - 2}} \tag{4}$$

where, $\bar{D}_{exp}$ and $\bar{D}_{ctrl}$ denote the adjusted mean competency scores for the experimental and control groups, respectively; s_{exp} and s_{ctrl} denote the sample standard deviations of the two groups; and n_{exp} and n_{ctrl} denote the sample sizes of the two groups. Effect size interpretation followed conventional threshold criteria, with $d \geq 0.2$ corresponding to a small effect, $d \geq 0.5$ to a medium effect, and $d \geq 0.8$ to a large effect. Through dimension-specific effect size calculations, the differential impact intensities of distinct mobile augmented reality interaction features on various design competencies could be identified, thereby revealing the underlying mechanisms linking technological application to professional competency development.

To ensure the measurement quality of the professional competency assessment scale for visual communication design, this study followed a structured procedure encompassing indicator generation, expert review, pilot testing, and reliability and validity evaluation. Initial items were developed based on the program's educational objectives, curriculum assessment criteria, and findings from preliminary interviews with teachers and students. Two rounds of expert reviews were then conducted, inviting specialists in visual communication design, design education, and educational measurement to evaluate item relevance, clarity of wording, and dimensional assignment. Items with overlapping semantics or insufficient discriminative power were removed, resulting in the final version of the scale. Pilot testing revealed that the overall Cronbach's α coefficient of the scale was 0.934, with subscale α coefficients for the five dimensions ranging from 0.842 to 0.901, indicating good internal consistency. The Kaiser-Meyer-Olkin measure was 0.908, and Bartlett's test of sphericity reached statistical significance ($p < 0.001$), confirming the suitability of the sample data for factor analysis. The factor structure obtained was consistent with the hypothesized five-dimensional theoretical framework—spatial form generation, dynamic visual expression, hierarchical information organization, interaction logic design, and creative ideation and execution—with standardized factor loadings for all items ranging from 0.642 to 0.873, all above acceptable thresholds. The intraclass correlation coefficient based on ratings from three professional teachers was 0.923, demonstrating high inter-rater consistency. These findings indicate that the scale possesses satisfactory content validity, construct validity, internal consistency, and inter-rater reliability, rendering it a suitable measurement instrument for assessing value-added gains in students' professional competencies and for comparing instructional effects across groups.

3 EXPERIMENTAL DESIGN AND RESULT ANALYSIS

3.1 Basic experimental setup

Second-year undergraduate students majoring in visual communication design at a university were selected as research participants. All participants had completed foundational professional coursework and had no prior experience with mobile augmented reality teaching tools. A between-groups quasi-experimental design was adopted, with 30 students assigned to the experimental group and 30 to the control group. Independent-samples t-tests revealed no significant differences in pre-test competency scores between the two groups, confirming baseline comparability. Experiments 1 through 4 were conducted within the context of a layout design course, while Experiment 5 was conducted within a motion graphics design course. Each experimental cycle lasted 8 weeks, with 2 class hours per week.

A pre-test–intervention–post-test research protocol was uniformly applied across all experiments. During the intervention phase, the experimental group received instruction supplemented by the mobile augmented reality teaching tool for both in-class and after-class practice, whereas the control group received instruction through conventional teaching methods employing standard multimedia courseware and two-dimensional demonstrations. Extraneous variables were strictly controlled throughout the experiments, with the same instructors, instructional content, total class hours, and assignment requirements maintained across both groups. All student design assignments were evaluated in a blind review manner, with three professional instructors holding associate professor or higher titles independently assigning scores, and the mean score was taken as the final score for each assignment, thereby ensuring the reliability and objectivity of the evaluation results.

The sample size was determined based on the research design and statistical power requirements. A priori power analysis was conducted with a significance level of 0.05, a statistical power of 0.80, and a medium effect size as the baseline parameters. The results indicated that a total of 60 participants, divided between the experimental and control groups, would satisfy the minimum sample requirement for the primary between-group effect tests. Prior to the study, all participants were provided with a complete explanation of the research purpose, instructional procedures, data usage, and their right to withdraw, and written informed consent was obtained. Student identifying information was anonymized through coding during the data compilation phase, and the research data were used solely for academic analysis, with no impact on course grades or routine teaching evaluations. To ensure consistency in the instructional intervention, both groups followed the same syllabus, learning tasks, class schedules, and assignment evaluation criteria. The instructors delivered the teaching according to a pre-established instructional plan, and the fidelity of implementation was verified through classroom records, completion of learning tasks, and system operation logs. No significant sample attrition that could compromise the statistical analysis occurred during the experiment; attendance rates and task completion rates did not differ significantly between the two groups, thereby mitigating the potential effects of sample selection bias, instructional implementation deviations, and cross-group contamination on the study findings.

3.2 System usability and user experience quality validation

This experiment was designed to examine the deployable usability and user experience level of the mobile augmented reality teaching tool and to determine whether the tool met the foundational conditions for routine classroom application. Upon completion of the experiments, participants in the experimental group were administered the system usability scale and the user experience questionnaire, and the obtained scores were compared against general benchmark values for mobile educational applications. The detailed results are presented in Figure 2.

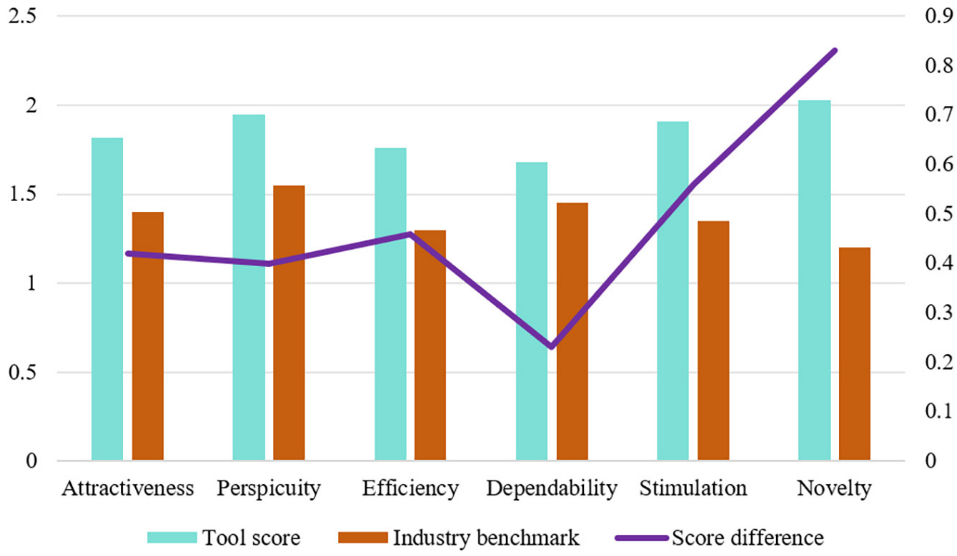

Fig. 2. User experience evaluation results of the mobile augmented reality teaching tool

The tool achieved a system usability scale total score of 78.25, exceeding both the acceptable usability threshold of 68 and the good usability threshold of 70, indicating that overall usability reached a good level and satisfied the basic operational requirements for classroom instruction. As shown in Figure 2, the scores of all user experience questionnaire dimensions exceeded the general benchmark values for mobile educational applications, with the most pronounced advantages observed in the novelty and stimulation dimensions, reflecting that the interactive modalities afforded by mobile augmented reality were capable of generating strong novelty and engagement among learners. The relatively modest increase in the dependability dimension score was primarily attributable to variations in mobile device hardware performance and ambient lighting conditions, yet the score remained within an acceptable range overall. These findings suggested that the tool possessed a favorable user experience foundation and could proceed to the subsequent pedagogical efficacy validation phase.

3.3 Overall design competency value-added effect validation

This experiment was designed to compare the value-added differences in overall design competency between the two instructional modalities and to validate the overall pedagogical efficacy of the mobile augmented reality teaching tool. Using the total score of the professional competency assessment scale for visual communication design as the evaluation metric, analysis of covariance was employed to control for the influence of pre-test baselines, and adjusted post-test mean scores were compared between the two groups, with effect sizes subsequently calculated. The detailed statistical results are presented in Table 1.

Table 1. Comparison of overall design competency value-added effects between the two groups

Group	Pre-Test Mean	Post-Test Mean	Adjusted Mean	Value-Added Mean	F-Value	p-Value	Cohen's d	Effect Size
Experimental group	62.37	79.52	79.41	17.15	32.64	<0.001	1.47	Large
Control group	61.89	70.46	70.57	8.57	–	–	–	–

Notes: Total scale score = 100 points; analysis of covariance was performed with group as the fixed factor and pre-test score as the covariate.

As shown in Table 1, following the 8-week instructional intervention, overall design competency improved in both groups, with the experimental group exhibiting a substantially greater value-added magnitude than the control group. The analysis of covariance results revealed that, after controlling for pre-test baselines, a highly significant difference in post-test scores was observed between the two groups, with an effect size of 1.47, corresponding to a large effect. These findings indicated that, compared with conventional multimedia-based instruction, the mobile augmented reality teaching tool was more effective in promoting overall design competency development among students, and the intervention effect of the tool demonstrated both statistical significance and practical applicability.

3.4 Differential analysis of dimension-specific competency improvements

This experiment was designed to decompose the improvement differences across distinct competency dimensions and to reveal the corresponding mechanisms through which mobile augmented reality interaction features are associated with specific design competencies. Value-added scores for the five competency dimensions were calculated separately for both groups, followed by between-group difference testing and effect size computation for each dimension. The detailed results are presented in Table 2.

As shown in Table 2, among the five competency dimensions, the largest improvement magnitude and effect size were observed for spatial form generation, followed by dynamic visual expression and hierarchical information organization, all of which reached large effect levels. This pattern directly corresponded to the three core interaction modalities of the tool. The three-dimensional preview interaction was directly implicated in the cultivation of spatial form generation, the dynamic hierarchical information visualization interaction corresponded to the enhancement of hierarchical information organization, and the interactive narration and dynamic feedback interaction supported the development of dynamic visual expression and interaction logic design. The between-group difference in creative ideation and execution did not reach statistical significance, with only a small effect size obtained, suggesting that the direct facilitative effect of the mobile augmented reality tool on divergent creative capacities was limited and that improvements in this dimension relied more heavily on design thinking training and knowledge accumulation, with the technological tool serving merely as an auxiliary support. The dimension-specific results not only validated the alignment between tool functional design and competency development objectives but also delineated the boundaries of technological efficacy.

Table 2. Comparison of dimension-specific design competency value-added scores and effect sizes

Competency Dimension	Experimental Group Value-Added	Control Group Value-Added	Between-Group Difference	t-Value	p-Value	Cohen's d	Effect Size
Spatial form generation	21.34	7.62	13.72	7.82	<0.001	1.81	Large
Dynamic visual expression	19.27	8.15	11.12	6.59	<0.001	1.53	Large
Hierarchical information organization	18.65	9.03	9.62	5.71	<0.001	1.32	Large
Interaction logic design	14.82	8.76	6.06	3.94	<0.001	0.91	Large
Creative ideation and execution	11.73	9.28	2.45	1.89	0.063	0.44	Small

Notes: Each dimension was scored on a 100-point scale; between-group difference tests were performed using independent-samples t-tests.

3.5 Ablation experiments on core interaction modalities

This experiment was designed to verify the independent marginal contributions of the three core interaction modalities and to examine the precision and necessity of the functional design. Three ablation experimental groups were established, with 20 participants in each group, and baseline competencies showed no significant differences from the full-featured group. In each ablation group, one of the three interaction functions—three-dimensional preview, dynamic hierarchical information visualization, or interactive narration and feedback—was selectively disabled, while all other instructional conditions were maintained consistently with the full-featured group. The value-added differences in the corresponding target competency dimensions were compared, and the experimental results are presented in Table 3.

As shown in Table 3, after the selective disabling of each of the three interaction functions, the value-added scores for the corresponding target competency dimensions all exhibited significant declines, with between-group differences reaching statistical significance in all cases. Among these, the largest reduction in value-added scores for spatial form generation was observed when the three-dimensional preview interaction was disabled, indicating that this interaction served as the core function underpinning the enhancement of spatial form generation. Similarly, the disabling of the other two interaction modalities also led to significant decreases in the corresponding competency gains. The ablation experiment results demonstrated that all three core interaction modalities functioned as independent driving factors for competency improvement, with no functional redundancy present, and that the functional design of the tool exhibited a high degree of precision and necessity. These findings also provided ancillary validation of the functional alignment advantages afforded by the design-thinking-driven development paradigm.

Table 3. Comparison of ablation experiment results for core interaction modalities

Ablation Group	Corresponding Target Competency	Full-Featured Group Value-Added	Ablation Group Value-Added	Value-Added Reduction	t-Value	p-Value
Three-dimensional preview disabled	Spatial form generation	21.34	12.76	8.58	4.27	<0.001
Hierarchical information visualization disabled	Hierarchical information organization	18.65	11.32	7.33	3.85	<0.001
Interactive narration and feedback disabled	Dynamic visual expression	19.27	12.89	6.38	3.31	0.002

3.6 Cross-course reusability validation of the methodological framework

This experiment was designed to examine the generalizability and adaptability of the integrated development-and-evaluation methodological framework proposed in this study across different design courses. The complete development workflow and evaluation system were reused in a motion graphics design course, with instructional intervention and efficacy validation conducted following the same experimental protocol. The tool usability and core competency improvement outcomes were compared between the two courses, with the results presented in Figure 3.

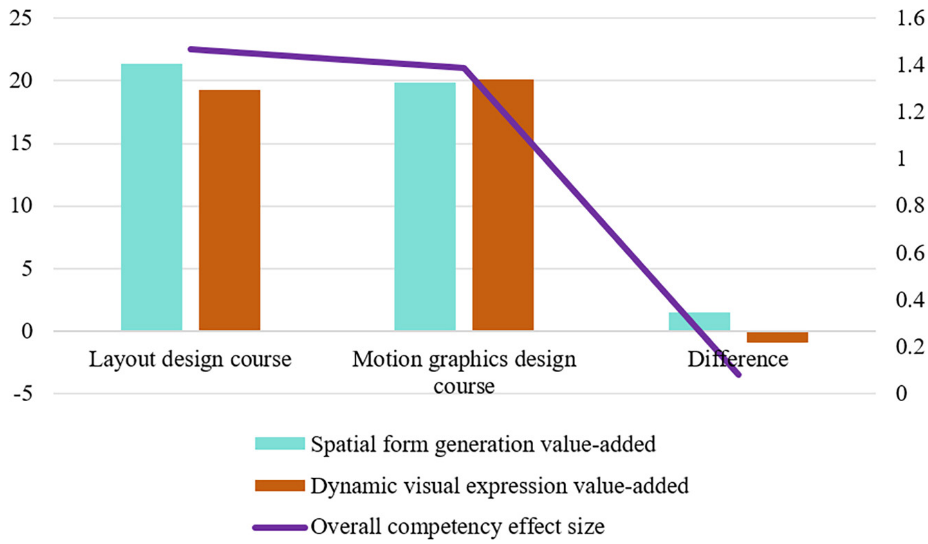

Fig. 3. Comparison of cross-course reusability outcomes of the methodological framework

As shown in Figure 3, after the methodological framework was reused in the motion graphics design course, the system usability scale score of the tool remained at a good level, with no notable difference from the score obtained in the layout design course. The value-added magnitudes for the core competency dimensions and the overall effect sizes both remained within comparable ranges, with the value-added score for dynamic visual expression being slightly higher in the motion graphics design course than in the layout design course, consistent with the respective competency emphasis of each course. These findings indicated that the proposed methodological framework maintained stable application effectiveness across different design courses, demonstrating favorable cross-course adaptability and reproducibility, and could serve as a standardized methodological reference for the large-scale dissemination of mobile augmented reality technologies in design education.

4 CONCLUSION

In response to the prevalent challenges of insufficient pedagogical alignment and the absence of professional competency assessment frameworks in mobile augmented reality educational applications, an integrated methodological framework for development and validation was established in this study. Design thinking methodology was incorporated into the full-cycle development of the teaching tool, resulting in a five-stage closed-loop development paradigm that ensured the alignment of tool functionalities with the core competency development objectives of visual communication design education. Based on the Unity 3D engine with integrated multi-source tracking technologies, three targeted interaction modalities were implemented, providing an immersive spatial cognition and interactive practice vehicle for design instruction. A dual-layer quantitative efficacy evaluation model was simultaneously constructed, enabling systematic measurement of both user experience quality and professional competence gains. The results from five experiments consistently demonstrated that the developed tool exhibited good usability and user experience and significantly facilitated the enhancement of multiple core design competencies among learners. All three interaction modalities were identified as independent driving factors for competency development, and the methodological framework demonstrated stable reproducibility across different course contexts, thereby offering a generalizable methodological reference for the deployment of mobile augmented reality technologies in design education.

Future research will further extend the applicability boundaries and technological depth of the proposed approach. On one hand, lightweight augmented reality algorithms for mobile devices will be optimized, and multimodal natural interaction modalities will be integrated so as to lower device performance barriers and enhance interactive immersion. On the other hand, artificial intelligence techniques will be introduced to construct dynamic learner competency profiles, enabling personalized adaptation of learning content and interaction pathways and thereby strengthening the precision of pedagogical interventions. Meanwhile, the application and validation of the methodological framework will be progressively extended to more design sub-disciplines and related fields, promoting the interdisciplinary and large-scale development of mobile augmented reality educational applications.

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6 AUTHOR

Ruiyi Li studied at the Beijing Institute of Graphic Communication from 2006 to 2010 and obtained her bachelor's degree in 2010. She has been working at the Department of Visual Communication, Hebei Art & Design Academy, since 2012. She has guided students in professional competitions, with her students winning national and provincial awards. She has published five academic papers and co-authored two textbooks on visual communication design. Her research interests cover visual communication design, cultural and creative product design, and the study of teaching models for visual communication design (E-mail: m15028297959@163.com).