Integrating Lenticular Motion Effects with WebAR for Smart Packaging: Design and Experimental Evaluation

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Abstract. Packaging design is increasingly expected to function as an interactive medium connecting physical products with digital information services. This paper proposes a smart packaging approach that integrates lenticular motion effects with Web-based augmented reality (WebAR) to construct a continuous physical-digital interaction experience without requiring a dedicated application. A three-layer multimodal framework is developed: a physical trigger layer based on optical motion, a media coupling layer that links package image features with browser-based recognition, and a digital enhancement layer that provides 3D animation, text, and audio. A rigid gift-box prototype was implemented through lenticular printing, QR-code access, MindAR.js, and A-Frame. A controlled experiment with 120 participants compared lenticular-only, WebAR-only, and coupled lenticular-WebAR interactions using eye-tracking data and questionnaire measures. The coupled condition produced longer fixation duration, higher immersion, and stronger brand identification than either single-medium condition ($p < 0.01$), showing that material optical cues can guide users naturally toward digital activation and improve the experiential value of smart packaging.

Keywords: Smart Packaging; WebAR; Lenticular Printing; User Experience; Multimodal Interaction

1 Introduction

Packaging design has moved beyond protection and containment toward brand communication, product narrative, and access to digital services. For cultural, craft, and brand-oriented products, the package is often the first interface through which users form expectations of quality and meaning. Augmented reality (AR) can enlarge this interface by overlaying animation, text, and sound on the physical package; however, many app-based solutions increase friction through downloads and authorization steps. WebAR lowers this threshold by opening AR content directly in a mobile browser, but it still depends on users noticing the entry point, orienting the package, and maintaining recognition stability.

Lenticular printing offers a complementary physical cue because its flip, zoom, or motion-like effect appears immediately when a package is tilted. The present study

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therefore asks how optical motion, package handling, image recognition, and WebAR content can be organized as one coherent interaction sequence rather than as separate effects. The contribution is a low-cost three-layer framework and a prototype evaluation that tests whether coupling lenticular motion with WebAR improves attention, immersion, and brand identification.

2 Related Work

AR/WebAR packaging. Smart packaging research has expanded the package from a protective container into an information interface that connects products, users, and services. AR packaging can add three-dimensional models, explanatory text, process animation, and audio guidance to printed surfaces, which is valuable when static graphics cannot fully express brand stories or craft processes [1]. WebAR is particularly suitable for retail contexts because interaction usually occurs quickly and users may not install a dedicated application. Nevertheless, browser-based AR still faces recognition stability, loading speed, and weak physical-digital continuity when the printed target is treated only as a marker[2].

Lenticular or optical-motion packaging. Lenticular printing uses a lens array and interlaced frame sequence to generate apparent motion as the viewing angle changes. This battery-free effect attracts gaze and encourages hand-based exploration before any digital interface is opened. From an embodied-cognition perspective, such manipulation is not only decorative; it supports perception-action coupling and prepares users to orient the package toward a camera [3]. However, lenticular graphics are limited in information capacity and cannot update content after printing.

Multimodal user experience and research gap. Packaging experience combines visual form, material texture, hand movement, spatial orientation, digital animation, sound, and text[4]. Prior studies show that engagement improves when sensory channels are organized around a clear task rather than presented as disconnected effects [5],. Existing work usually discusses smart packaging, WebAR, and optical printing separately; the transition from physical visual cue to digital activation is often reduced to scanning a code. Few studies specify how angle-change or hand-tilt actions produce a motion cue, how that cue guides camera orientation, how recognizable image features support tracking, and how digital content should respond after recognition[6]. This gap motivates the proposed framework.

Accordingly, this study treats scanning as a designed perceptual and behavioral process. The physical surface should first invite manipulation, the recognition target should transform this manipulation into a stable camera pose, and the digital layer should return feedback that is spatially and semantically connected with the printed package. This organization strengthens the theoretical basis of the paper and directly responds to the limitation that previous studies seldom explain the physical-to-digital transition mechanism[7].

3 Proposed Framework

The framework defines the transition from physical perception to digital augmentation as a sequence of input-output transformations. Each layer receives a specific user or system input, uses defined design elements, and produces an output that prepares the next layer, as summarized in Table 1.

Table 1. Operational definition of the three-layer multimodal framework.

Layer	Input	Key design elements	Output and function
Physical trigger	Viewing-angle change; hand tilt; package rotation	Lenticular frame sequence; lens direction; motion rhythm; contrast; placement near target image	Motion-like visual cue and manipulation intention; attracts gaze and guides embodied exploration
Media coupling	Camera capture after QR-code entry	Stable target image; high-contrast contours; irregular texture; logo or boundary features; MindAR threshold	Recognition state, camera pose, and AR anchor; bridges physical cue and browser-based activation
Digital enhancement	Recognized target and pose information	A-Frame scene; glTF model; key-frame animation; text panels; audio; targetFound/targetLost events	3D animation, text, and audio; extends product information, brand narrative, and sensory experience

Through this structure, the lenticular effect first motivates viewing and handling, the media coupling layer converts the package image into a trackable digital anchor, and the digital layer provides deeper narrative and informational content. The framework therefore treats smart packaging as a designed behavioral bridge from material stimulus to WebAR engagement.

The three layers are interdependent rather than parallel. If the physical trigger lacks contrast or motion rhythm, users may not initiate exploration; if the media coupling layer contains unstable visual features, the WebAR scene cannot remain anchored; if the digital enhancement layer is overloaded, users may perceive the interaction as fragmented. The design task is therefore to balance optical attraction, recognition robustness, and narrative depth within a short retail interaction cycle.

4 Prototype Implementation

A rigid gift box (220 mm x 160 mm x 65 mm) was produced as the prototype carrier. The front panel presented a lenticular sequence describing material preparation, weaving, forming, and finished product display; a QR code on the side panel opened the HTTPS WebAR page. Users first noticed the optical motion, tilted or rotated the box, scanned the QR code, and then aligned the front image with the mobile camera to activate the AR scene.

The lenticular artwork was generated from normalized process images and interlaced according to the lens direction. Because strong optical variation can reduce recognition stability, the AR target was created from the non-interlaced front-panel artwork. It retained logo contours, border patterns, and high-contrast weaving textures, while excluding large blank areas, specular highlights, the QR code, and small elements that changed strongly with angle. Candidate targets were tested at common viewing distances and tilt angles under indoor lighting before compilation into a MindAR .mind file.

The WebAR module used MindAR.js for image tracking and A-Frame for scene construction. After page loading, the asset manager loaded the .mind file, compressed texture maps, a low-polygon glTF craft-scene model, text panels, and an audio file. The targetFound event displayed animation, product information, and audio guidance; targetLost paused or hid the scene until recognition resumed. Prototype verification was conducted on iOS Safari and Android Chrome browsers. Model complexity was controlled to maintain browser performance and make the system reproducible for low-cost packaging applications, as shown in Fig. 1.

To support reproducibility, the implementation followed four constraints. First, AR entry relied only on a QR code and an HTTPS page, so no dedicated application or plug-in was required. Second, the recognition target was separated from the lenticular interlaced image to reduce feature drift caused by angle-dependent optical change. Third, the digital scene used a small number of animated objects and planar information panels rather than dense geometry. Fourth, the audio narrative was triggered after user entry to comply with mobile browser autoplay restrictions. These decisions link the design method with practical deployment conditions in smart packaging.

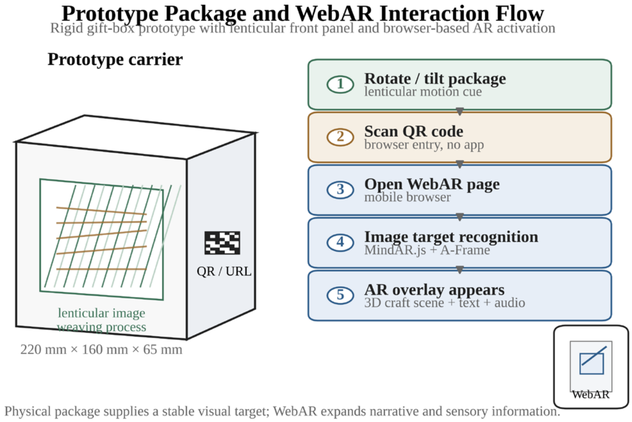

Fig. 1. Prototype package and WebAR interaction flow.

5 Experimental Design

A controlled between-subjects experiment evaluated the user experience effects of the proposed system. A total of 120 university students and young adult consumers were randomly assigned to three equal groups: lenticular-only interaction, WebAR-only interaction, and coupled lenticular-WebAR interaction. Participants were 18-35 years old (M = 23.6, SD = 3.8) and reported normal or corrected-to-normal vision; those who could not complete eye-tracking calibration were excluded.

Basic sample information was collected before the task to control possible confounds. The sample included 46 participants with design-related education and 74 without. Prior AR experience was distributed as none (33), occasional (58), and frequent (29). Mean familiarity with smart packaging was 2.81 ± 0.89 and familiarity with the product category was 3.06 ± 0.84 on five-point scales. The three groups showed no significant differences in these background variables ($p > 0.05$).

The lenticular-only group observed the printed package and optical motion without opening AR; the WebAR-only group accessed the same digital content with a static target; the coupled group completed the full process. Each participant interacted with the prototype for three minutes under controlled lighting, viewing distance, and task duration. Eye-tracking data were recorded with a Tobii Pro Nano, and questionnaires measured immersion, brand identification, and cognitive load on seven-point scales.

The dependent variables were selected to cover behavioral attention, subjective engagement, brand communication, and perceived effort. Fixation duration was used as the main attention indicator, immersion and brand identification were treated as experiential outcomes, and cognitive load was included to verify that the coupling mechanism did not improve experience at the cost of excessive mental effort. One-way ANOVA and post-hoc comparisons were used to compare the three conditions.

6 Results and Discussion

As shown in the Fig. 2. ANOVA results showed significant differences among the three conditions. The coupled lenticular-WebAR condition achieved the longest fixation duration and highest immersion score ($p < 0.01$), and participants also reported stronger brand identification than in either single-medium condition. Cognitive load remained within an acceptable range, indicating that the additional physical-digital sequence did not create excessive burden.

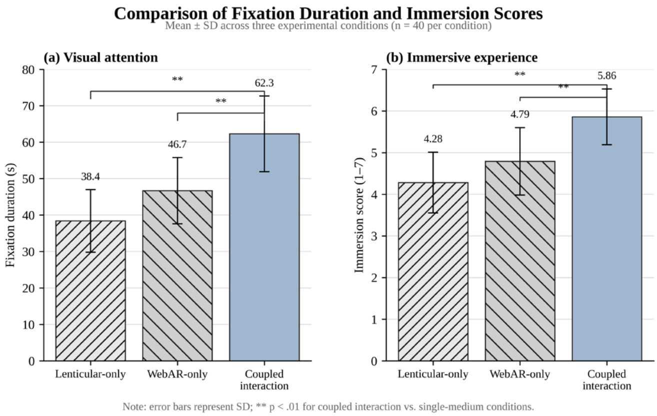

Fig. 2. Comparison of fixation duration and immersion scores.

Table 2. Descriptive statistics of the three conditions.

Condition	n	Fixation duration (s)	Immersion score	Brand identification	Cognitive load
Lenticular-only	40	38.4 ± 8.6	4.28 ± 0.73	4.22 ± 0.76	3.64 ± 0.69
WebAR-only	40	46.7 ± 9.1	4.79 ± 0.81	4.58 ± 0.82	4.08 ± 0.77
Coupled interaction	40	62.3 ± 10.4	5.86 ± 0.67	5.72 ± 0.70	3.76 ± 0.72

As shown in Table 2. These results support the physical-digital transition mechanism. Lenticular-only interaction attracted attention but lacked information depth, while WebAR-only interaction provided digital content but offered weaker motivation for package orientation. In the coupled condition, the optical cue encouraged users to handle the box and attend to the front image, making QR-code access and target recognition more coherent. The integration therefore improved attention, immersion, and brand communication without causing an unacceptable increase in cognitive load.

7 Conclusion

This study proposed and evaluated a low-cost smart packaging strategy that integrates lenticular motion effects with WebAR. By specifying the inputs, design elements, outputs, and functions of the physical trigger, media coupling, and digital enhancement layers, the paper operationalizes the transition from material visual cue to digital activation. The prototype demonstrated how lenticular printing, QR-code access, MindAR.js, A-Frame, lightweight 3D assets, text, and audio can transform a printed package into a browser-based storytelling interface. Experimental results from 120 participants confirmed that the coupled condition improved fixation duration, immersion, and brand identification compared with lenticular-only and WebAR-only interactions. Future research will test the approach in retail environments and explore personalized AR content and AI-assisted recommendations.

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