

An Augmented Reality Application for Ancient Human Fossil Education in Digital Learning: Design and User Experience Evaluation

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ABSTRACT

Learning resources on ancient human fossils are still largely dominated by two-dimensional representations and limited physical access to museum collections, which restrict interactive and contextual learning experiences. This research seeks to design and assess FOSSERA, an Augmented Reality (AR)-based educational application created to display three-dimensional visualizations of ancient human fossil skulls. The application was developed following the Multimedia Development Life Cycle (MDLC) Method, which consists of the phases of conceptualization, design, material collection, assembly, testing, and distribution. User experience evaluation was conducted through a quantitative approach using the User Experience Questionnaire (UEQ) involving 28 respondents who operated the application on Android devices. The evaluation results show that FOSSERA achieved positive mean scores across all six UEQ dimensions. The dimensions of Attractiveness, Perspicuity, and Efficiency obtained relatively high scores, indicating that the application is perceived as visually appealing, easy to understand, and efficient to use. Meanwhile, the dimensions of Dependability, Stimulation, and Novelty received comparatively lower scores, suggesting the need for further improvement in system stability, interactive engagement, and feature innovation. Overall, the findings confirm that the implementation of AR technology in FOSSERA provides a positive user experience and contributes to the development of interactive digital learning media in educational environments.



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I. INTRODUCTION

The widespread integration of immersive technologies in the educational sector has generated growing attention toward Augmented Reality (AR) as an interactive instructional medium that can improve conceptual comprehension and learner engagement. AR overlays virtual objects onto real environments, providing experiential learning experiences that are difficult to achieve with traditional two-dimensional materials [1]. Empirical studies indicate that mobile AR applications can improve learner motivation, spatial reasoning, and learning outcomes across multiple disciplines [2].

Recent research has emphasized the importance of user experience (UX) in AR educational applications. UX

evaluation provides critical insight into how users perceive and interact with AR systems, yet standardized measurement in educational AR remains limited [3]. Several studies have applied the User Experience Questionnaire (UEQ) to assess AR interfaces and reported generally positive usability results [4]. However, most studies focus on general subjects such as science or language learning, while AR applications for ancient human fossil education remain underexplored [5].

A few researchers have investigated AR user experience in educational contexts; however, there have been limited studies concerned with AR applications specifically designed for paleoanthropology education and evaluated systematically using UEQ [6]. In addition, the relationship between a structured multimedia development process such as MDLC and the resulting UX quality has not been sufficiently

addressed [7]. Previous AR learning studies mainly emphasize technical implementation or learning effectiveness, with less attention given to user acceptance of domain-specific content such as morphological visualization of ancient human skulls [8]. Recent large-scale empirical research has confirmed that AR-supported instruction produces statistically significant improvements in students' learning outcomes compared to conventional instructional approaches. The interactive visualization and contextual immersion facilitated by AR contribute to deeper conceptual processing and improved academic achievement across educational levels [9].

Furthermore, recent investigations highlight that the acceptance of AR learning media is strongly influenced by content characteristics and interaction design [10]. Nevertheless, empirical evidence regarding how users perceive marker-based AR applications presenting anthropological fossil information—such as skull morphology, discovery location, and cranial characteristics—remains scarce [11]. This gap indicates the need for a focused evaluation of user experience acceptance in AR applications dedicated to ancient human fossil education.

Therefore, this research intends to develop and evaluate FOSSERA, a marker-based AR application that visualizes three-dimensional ancient human skull models and provides structured anthropological information. The objectives of this study are to (1) develop an AR application using the MDLC approach, (2) implement 3D fossil skull visualization on Android devices with interactive information features, and (3) measure user experience acceptance using the UEQ instrument to determine whether the application is well received by users [8], [10], [11].

To ensure a focused and manageable scope, this study defines several research boundaries. First, the objects displayed in the AR application are limited to selected ancient human fossil skulls and do not encompass the full diversity of fossil species discovered globally. The visualization emphasizes cranial morphology as the primary learning object rather than presenting complete skeletal reconstructions. Second, the technological implementation is confined to marker-based Augmented Reality, meaning that markerless AR systems, spatial tracking AR, or other immersive technologies such as Virtual Reality (VR) are beyond the scope of this research. Third, the fossil content presented in the application is restricted to general educational information, including discovery location and prominent cranial characteristics, without engaging in detailed anthropological, evolutionary, or medical analysis. Finally, this study concentrates exclusively on evaluating user experience acceptance using the UEQ instrument and does not examine the impact of the application on measurable learning outcomes or academic achievement. These limitations are established to maintain clarity of research focus while providing a foundation for future, more comprehensive investigations.

II. RESEARCH METHOD

This study employs the Research and Development (R&D) method aimed at producing and evaluating an Augmented Reality (AR)-based learning application named FOSSERA. The application development process follows the Multimedia Development Life Cycle (MDLC) model. The MDLC method was selected because it is considered effective for the development of interactive multimedia applications and has been widely applied in recent studies on educational augmented reality application development [12], [13].

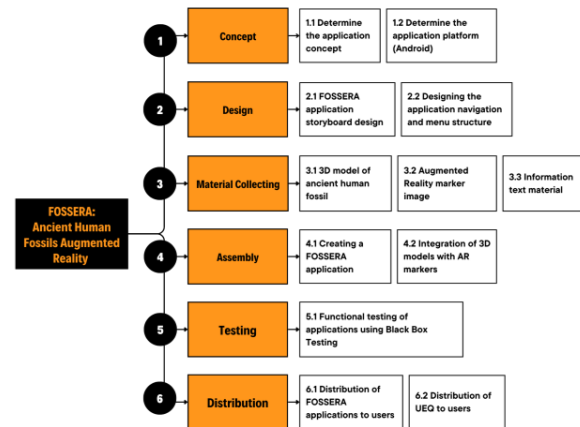


Figure 1. Work Breakdown Structure (WBS)

The Work Breakdown Structure (WBS) of the FOSSERA development is organized into six main phases based on the Multimedia Development Life Cycle (MDLC): concept, design, material collecting, assembly, testing, and distribution [14]. The concept phase defines the application objectives and target platforms. The design phase focuses on storyboard development and navigation structure. Material collecting involves gathering 3D fossil models, augmented reality markers, and supporting textual content. The assembly phase integrates all assets and implements the augmented reality functionality. Testing is conducted using black box testing to ensure that all features function as intended. Finally, the distribution phase includes application deployment and the dissemination of the User Experience Questionnaire (UEQ) for user experience evaluation [15].

A. Concept

At the Concept stage, the fundamental framework for application development is defined, including the determination of system objectives and the target platform. In this phase, a use case diagram is developed to identify the involved actors and the primary interactions between users and the FOSSERA system. Additionally, a system flowchart is created to illustrate the overall application process, starting from user access to the visualization of augmented reality based fossil objects. These models serve as an initial representation of system behavior before proceeding to the interface design and navigation structure stages. Through this approach, the functional requirements of the application can

be systematically defined in accordance with the scope established in the Work Breakdown Structure (WBS).

1. Flowchart

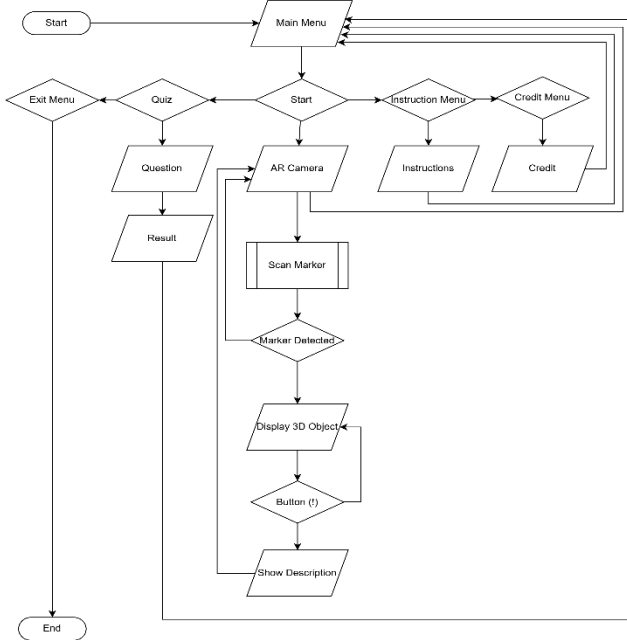


Figure 2. Fossera Application Flowchart

The flowchart of the FOSSERA application illustrates the sequential logical flow of system processes from initialization to augmented reality visualization. Flowcharts are widely used in system design to represent procedural workflows and decision structures, helping clarify system logic and user interaction paths prior to implementation [16]. The process starts at the Start node and proceeds to the Main Menu, where users select one of four options: Instruction, Credit, Start, or Exit. Selecting Instruction or Credit displays the respective information pages and returns to the main menu, while Exit terminates the application. When the user chooses to Start, the system activates the AR camera and performs marker scanning. A decision evaluates marker detection; unsuccessful detection results in repeated scanning, whereas successful detection leads to rendering the three-dimensional fossil object and presenting descriptive information to users, reflecting the logical flow and interaction in the AR-based educational application.

2. Use Case

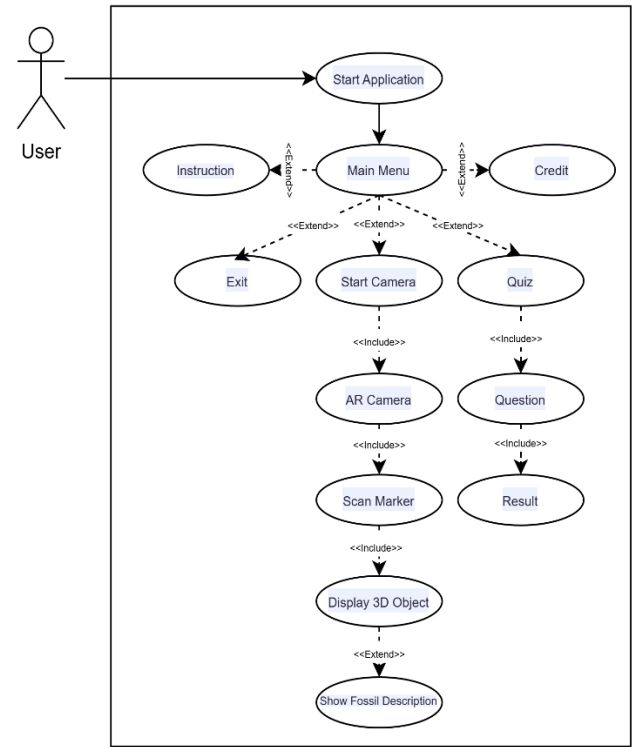


Figure 3. Fossera Application Use Case Diagram

A use case diagram is used to model the functional interaction between users and the FOSSERA augmented reality application. In software engineering, use case diagrams are a fundamental technique in Unified Modeling Language (UML) for identifying actors, system boundaries, and high-level system functionality, assisting in early-stage requirement modeling and analysis in application design [17]. In this study, the user is defined as the primary actor interacting with FOSSERA through the Main Menu, which serves as the central navigation interface. Users can access core functions, including Start Camera, Instruction, Credit, and Exit. The Start Camera use case includes included processes such as AR camera activation and marker scanning to display three-dimensional fossil objects. The Show Fossil Description use case extends this interaction by providing supplementary text information tied to the displayed object.

B. Design

At the Design stage, system planning is conducted based on the results of the conceptual phase by developing the application storyboard and designing the navigation structure and menu layout of the FOSSERA application. This stage aims to visualize user interaction flows and interface layouts as a foundation prior to the implementation process.

C. Material Collecting

The Material Collecting stage focuses on gathering and preparing all required learning assets, including three dimensional models of ancient human fossils, augmented

reality marker images, and supporting textual information. All materials are selected and adapted to ensure educational relevance and technical compatibility with the augmented reality application.

D. Assembly

During the Assembly stage, all design elements and materials are integrated into the development platform to produce a functional FOSSERA application. This process includes application development, integration of 3D fossil models with AR markers, and implementation of user interaction features and navigation systems.

E. Testing

The Testing stage was conducted using the Black Box Testing method to verify that all features of the FOSSERA application function in accordance with the predetermined specifications. This process focused on examining input–output conformity without analyzing the internal program structure, with the aim of identifying functional errors and ensuring system stability prior to user deployment.

F. Distribution

The Distribution stage involved delivering the FOSSERA application to target users and administering the User Experience Questionnaire (UEQ) to obtain empirical data regarding user perceptions. This stage served as the basis for evaluating the overall quality of the application, particularly in terms of usability and user experience after real-world interaction.

The User Experience Questionnaire (UEQ) is a standardized and empirically validated instrument widely used to measure user experience in interactive systems. Previous studies have confirmed its construct validity across six dimensions and demonstrated satisfactory internal consistency reliability, with Cronbach's alpha values generally exceeding the acceptable threshold of 0.70. Therefore, the use of UEQ in this study is considered methodologically appropriate and reliable for evaluating the user experience of the FOSSERA application.

III. RESULT AND DISCUSSION

This section presents the results of the development and evaluation of the FOSSERA augmented reality application. The results emphasize the implementation of the application as well as the outcomes of the user experience evaluation using the User Experience Questionnaire (UEQ), which was administered to students aged 15–22 years after they interacted with the application. The discussion interprets the findings of the user experience evaluation by relating the UEQ dimensions to the functional and design characteristics of the FOSSERA application. Furthermore, this section highlights potential areas for improvement to enhance the overall quality and usability of the application.

A. Concept

Table 1 summarizes the concept attributes of the FOSSERA application, which represent the core characteristics and scope of the developed system. These attributes define the application's objectives, target users, learning objects, content focus, and the platform used as a foundation for evaluating the development results.

TABLE I
FOSSERA CONCEPT

Concept Attribute	Description
Title	FOSSERA (Fossil Era)
Goals	To develop an augmented reality–based learning application focused on ancient human fossils and to assess the user experience using the User Experience Questionnaire (UEQ).
Target	Students aged 15–22 years, including high school and undergraduate students, as the primary users of the application.
Object	3D models of ancient human fossil skulls
Content	Educational content related to ancient human fossils, including interactive 3D skull visualizations and supporting textual descriptions presented through augmented reality.
Platform Used	Minimum Android 7.0 (API Level 24)

Based on the concept attributes presented in Table 1, FOSSERA is positioned as an augmented reality–based educational application that emphasizes interactive visualization of ancient human fossil skulls. The defined target users and content focus ensure that the application supports both educational objectives and user experience evaluation, serving as a basis for analyzing the functional implementation and UEQ results discussed in subsequent subsections.

B. Design

At the Design stage, the initial design of the FOSSERA application is developed by defining the navigation structure and creating storyboards as the visual and functional foundation of the application. These components serve as the main reference prior to the implementation of the augmented reality system. The navigation structure defines the user interaction flow from application launch to three-dimensional fossil visualization, while the storyboard illustrates interface layouts and system responses to user actions. All design results are documented in the form of figures and tables presented in the following sections, providing a clear reference for development and preliminary evaluation of the application's usability and educational effectiveness.

This application has been applied established theories in multimedia learning and user experience. Based on the Multimedia Learning Theory proposed by Richard E. Mayer

[18], combining visual and textual information enhances understanding. Furthermore, based on the pragmatic–hedonic quality perspective of the User Experience Questionnaire (UEQ) Consortium framework, FOSSERA demonstrates strong capability in supporting users to achieve their learning objectives effectively and comfortably through its AR-based visualization features.

1. Navigation Structure

The navigation structure is designed to illustrate the relationships between menus and features in the FOSSERA application. It serves as a system framework that enables users to access the main application functions in a logical and intuitive manner. The visualization of the navigation structure is presented in Figure 4.

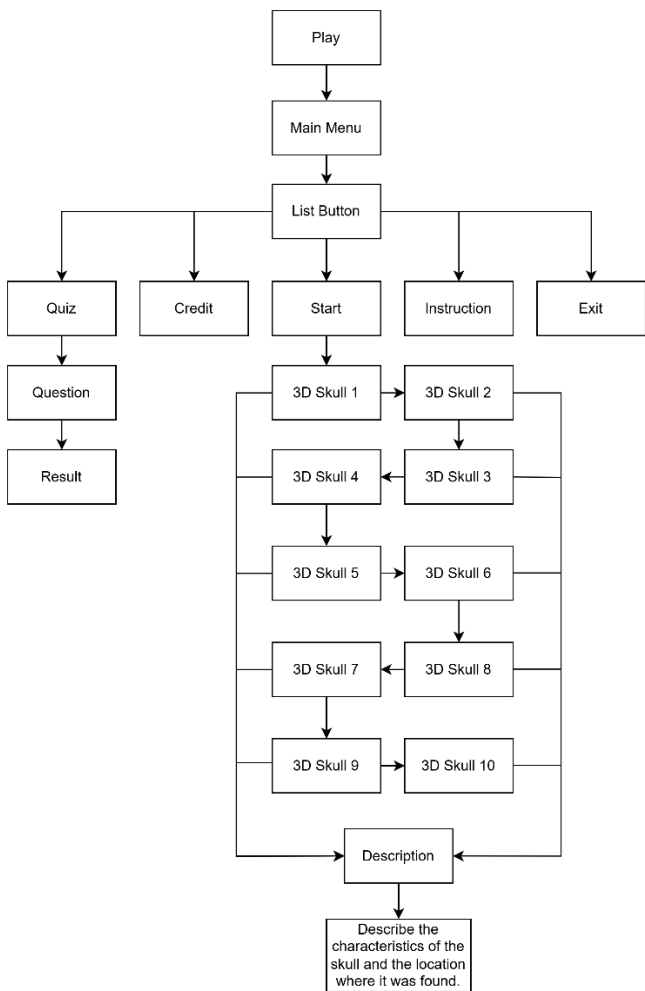


Figure 4. Fossera Application Navigation Structure

2. Storyboard Design

The storyboard is developed as the visual foundation and operational framework of the FOSSERA application, representing the system flow and user interactions in a systematic manner. The storyboard design applies

usercentered design principles to ensure that each interface and navigation element effectively supports the learning process.

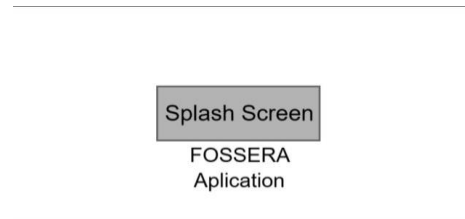


Figure 5. Splash Screen Dsisplay

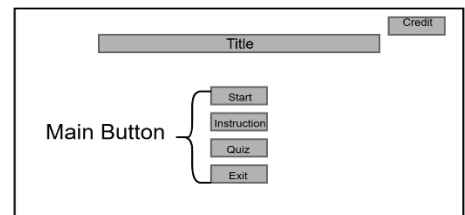


Figure 6. Main Menu Dsisplay

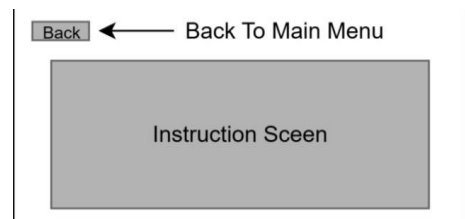


Figure 7. Instruction Menu Dsisplay

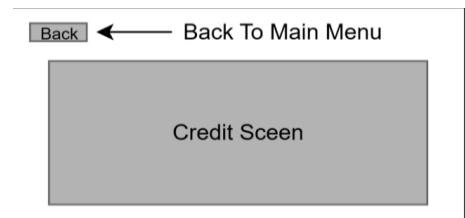


Figure 8. Credit Menu Dsisplay

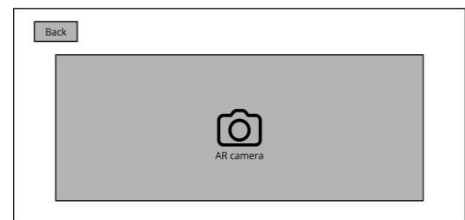


Figure 9. Marker Detection Process

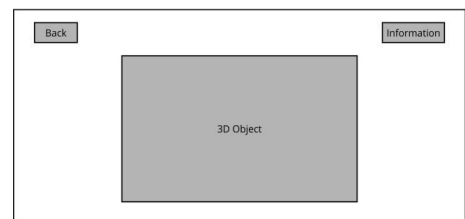


Figure 10. Visualization of 3D Objects and Information Buttons

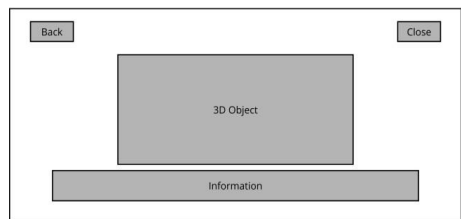


Figure 11. Visualization of 3D Objects and Associated Information

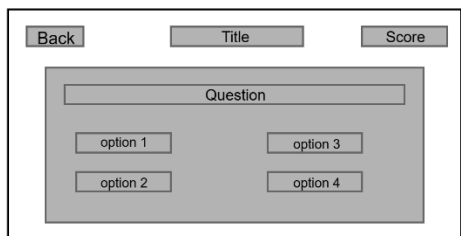


Figure 12. Quiz Menu Display

C. Material Collecting

The Material Collecting stage involves identifying and gathering all resources required as educational content for the FOSSERA application. This process is conducted through a literature review by examining various academic sources, including journals, articles, and books, to obtain accurate information related to ancient human fossil skulls. The collected materials include images, augmented reality markers, and three-dimensional fossil skull models. All visual assets and 3D objects are prepared to be processed and integrated during the Assembly stage using the Unity development environment. The 3D fossil models are developed and optimized using Blender and exported in.fbx format, while two-dimensional assets such as markers and supporting images are prepared in .png format. All collected assets are subsequently imported into each application scene to support comprehensive visualization and interactivity within the FOSSERA augmented reality application.

The following table summarizes selected hominin fossils, including their estimated age, geographic location, and key cranial characteristics:

TABLE II
FOSSIL INFORMATION

No	Fossil Name (Location)	Estimated Age & Location	Cranial Characteristics
1	Peking Man (Zhoukoudian, China)	~700,000–200,000 years ago, near Beijing, China	Long and low cranial vault, receding forehead, very thick supraorbital brow ridge, thick cranial bones, absence of a true chin; typical <i>Homo erectus</i> morphology.
2	Dali Man (Dali County, China)	~300,000–200,000 years ago, China	Mosaic of archaic and more derived traits; relatively large cranial capacity, thick brow

	Shaanxi, China)		ridge, face less robust than <i>H. erectus</i> ; often associated with archaic humans approaching early <i>Homo sapiens</i> .
3	Harbin Cranium (“Dragon Man”, Harbin, China)	≥146,000 years ago, northeastern China	Large and elongated cranium, massive brow ridges, broad face, cranial capacity ~1,400 cc; archaic Asian features with brain size comparable to modern humans.
4	Yunxian Man (Hubei, China)	~1 million years ago (possibly older), China	Long and low skull shape, thick brow ridges, robust cranial bones; classified within early Asian <i>Homo erectus</i> .
5	Homo erectus Asia (Indonesia/Java/Southeast Asia)	~1.6 million–200,000 years ago	Low cranial vault, receding forehead, pronounced brow ridges, thick cranial bones and robust mandible, no chin; characteristic of Asian <i>Homo erectus</i> .
6	Wajak Crania (East Java, Indonesia)	~37,000–28,000 years ago	Higher and more rounded cranial vault, reduced facial robusticity, presence of a chin; classified as early <i>Homo sapiens</i> in Indonesia.
7	Sangiran / Trinil (Java Man, Indonesia)	~1.5 million–500,000 years ago, Java	Very thick cranial bones, large brow ridges, long and low skull, cranial capacity ~900–1,100 cc; classic Javanese <i>Homo erectus</i> .
8	Florisbad Skull (Free State, South Africa)	~260,000 years ago, South Africa	Higher forehead than <i>H. erectus</i> , moderately developed brow ridges, cranial capacity ~1,400 cc; transitional morphology toward early <i>Homo sapiens</i> .
9	Skhul & Qafzeh Early Modern Humans (Israel – Levant)	~120,000–90,000 years ago, Israel	High and rounded cranial vault, prominent forehead, reduced brow ridges compared to archaic hominins, relatively flat face; early anatomically modern <i>Homo sapiens</i> .
10	Peștera cu Oase (Romania)	~40,000–37,000 years ago, Romania	High and rounded skull, well-developed chin, but retains some archaic facial traits; early modern human in Europe with mixed morphological features.

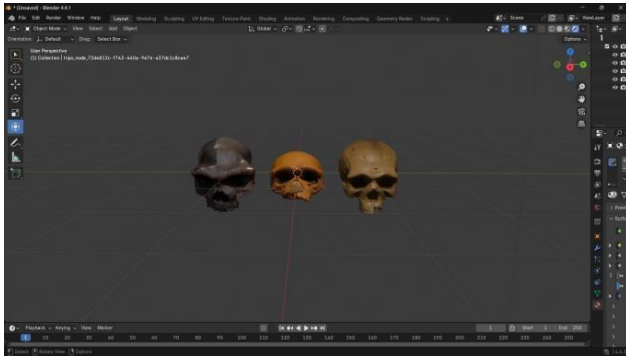


Figure 13. 3D Object Modeling with Blender

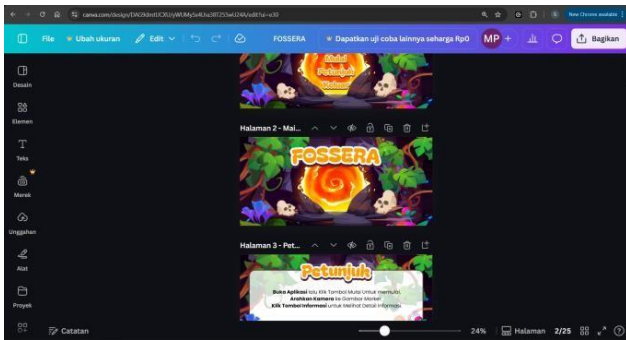


Figure 14. Development of 2D Visual Assets with Canva

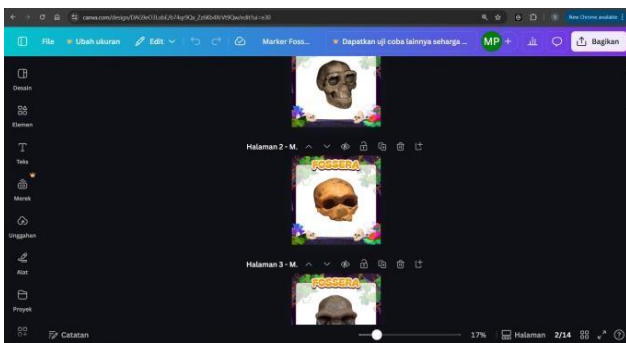


Figure 15. Production of 2D Marker Visuals through Canva

D. Assembly

After the Material Collecting stage was completed, all collected assets were integrated during the application development process of FOSSERA using Unity 2022.3.60f1. This stage focused on assembling the application components based on the design specifications to produce a functional augmented reality learning application. The three dimensional models of ancient human fossil skulls, which were previously created and exported from Blender, were imported into the Unity development environment and arranged within a 3D scene. Marker data integration was carried out using the Vuforia SDK as the augmented reality database, enabling accurate marker recognition and tracking within the application. Through this integration, the system is able to detect markers and display the corresponding 3D fossil

models in real time, forming the core functionality of the FOSSERA application.



Figure 16. Creating AR Application Using Unity

E. Testing

The testing phase was conducted to verify that all functions of the FOSSERA application performed according to the predetermined design and functional specifications. Functional evaluation employed the Black Box Testing approach, which emphasizes validating input–output responses without examining the internal program structure. The findings indicate that all core features—including menu navigation, augmented reality scanning, information presentation, and application controls—operated as intended. Each user action generated the appropriate system response, demonstrating that the application is functionally stable and ready for subsequent user experience assessment using the User Experience Questionnaire (UEQ).

TABLE III
BLACK BOX TESTING

Feature	Testing Scenario	Expected Output	Testing Result
Main Menu – Start Button	User selects the Start menu to access the AR module	The system activates the smartphone camera and initializes the marker recognition process	Successful
Augmented Reality Scanning	The camera is directed toward a valid marker	A three-dimensional fossil model is rendered above the detected marker and the information button becomes available	Successful
Information Button	User presses the information button after the 3D object appears	A descriptive window displaying fossil name, discovery location, and key characteristics is presented	Successful

Object Rotation (Single Touch)	User drags one finger across the screen after the 3D object appears	The 3D fossil model rotates responsively according to the direction of finger movement	Successful
Object Scaling (Two-Finger Gesture)	User performs a pinch-in or pinch-out gesture on the 3D object	The 3D fossil model scales proportionally within predefined size limits	Successful
Back Button (AR Page)	User presses the back button on the AR scanning screen	The system navigates to the instruction page	Successful
Main Menu – Instruction Button	User selects the Instruction menu	The application displays the usage guidance page	Successful
Back Navigation (Instruction Page)	User presses back on the instruction page	The system returns to the main menu	Successful
Main Menu – Credit Button	User selects the Credit menu	The application displays the credit information page	Successful
Back Button (Credit Page)	User presses back on the credit page	The system navigates to the main menu	Successful
Main Menu – Quiz Button	User selects the Quiz feature	The system opens the quiz interface and displays the first question with answer options and initial score	Successful
Correct Answer Selection	User selects the correct answer	The system displays a correct indicator and adds 25 points to the score	Successful
Incorrect Answer Selection	User selects an incorrect answer	The system displays an incorrect indicator and the score remains unchanged	Successful
Automatic Question Transition	User selects an answer	The system automatically displays the next question	Successful
Quiz Completion and Score Calculation	User completes all questions	The system calculates and displays the final score accurately	Successful
Main Menu – Exit Button	User selects the Exit command	The application closes and returns to the device home screen	Successful

Table II presents the outcomes of functional testing carried out through the Black Box approach. The results demonstrate that all core system components including AR camera activation, real-time rendering of 3D fossil models, contextual information pop-ups, and menu-based navigation controls—operated in full accordance with the predefined functional requirements. Each tested interaction produced the expected system response without observable functional errors. Supplementary documentation of the testing procedures is presented in Figures 16–20, which visually substantiate the successful execution of each feature. These findings indicate that the FOSSERA application achieves a high level of functional stability and ensures a smooth, reliable user interaction flow prior to user experience evaluation.



Figure 17. Main Menu Testing



Figure 18. Quiz Menu Testing

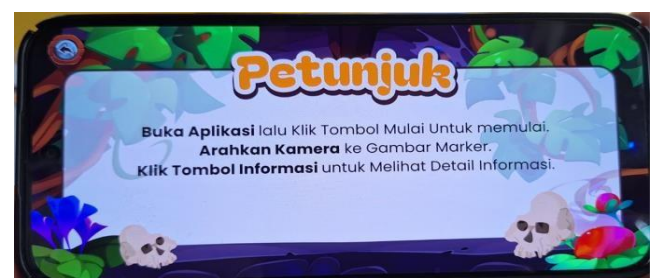


Figure 19. Instruction Menu Testing

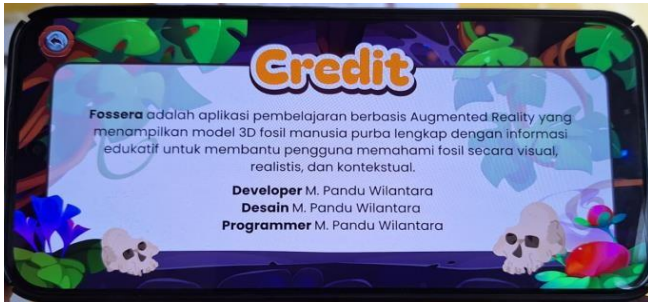


Figure 20. Credit Menu Testing

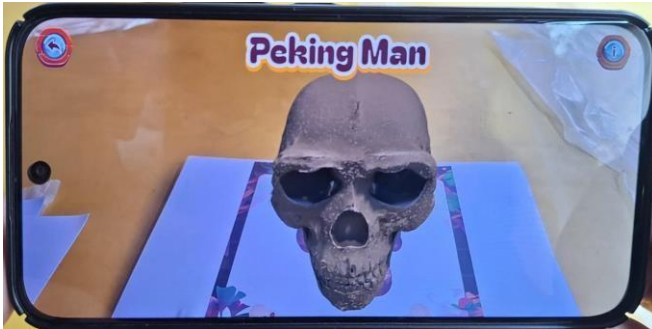


Figure 21. AR Marker Scan Testing



Figure 22. Button Information (i) Testing

F. Distribution

The Distribution stage involved deploying the FOSSERA application to students aged 15–22 years for practical use and evaluation. The application was installed on Android devices and distributed online to facilitate user access during the testing period. At this stage, the User Experience Questionnaire (UEQ) was administered to 28 respondents to evaluate user Attractiveness, experience Perspicuity, across six Efficiency, dimensions: Dependability, Stimulation, and Novelty. The collected data served as the basis for analyzing the usability and overall user experience of the application.

TABLE IV
UEQ SCALES

UEQ Scales (Mean and Variance)		
Attractiveness	1,756	0,91
Perspicuity	1,670	1,11
Efficiency	1,652	1,00
Dependability	1,589	0,95
Stimulation	1,545	0,99
Novelty	1,205	1,37

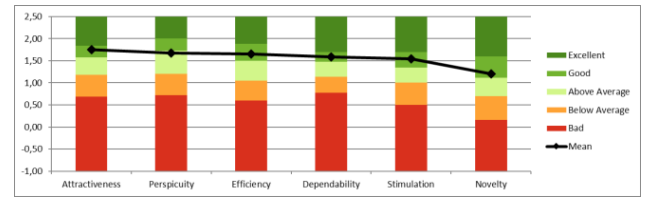


Figure 23. UEQ Dimension Benchmark Chart

The evaluation of the FOSSERA application was conducted using the User Experience Questionnaire (UEQ) involving 28 respondents aged 15–22 years. Referring to the UEQ benchmark interpretation guidelines, a mean score above 0.8 indicates a positive evaluation, while values exceeding 1.5 are generally categorized within the “Good” to “Above Average” classification when compared to established product datasets. Based on this benchmark framework, all six UEQ dimensions of FOSSERA demonstrate positive user perception.

The Attractiveness dimension obtained the highest mean score (1.756; variance 0.91), positioning it within the “Good” category. This result indicates that users formed a favorable overall impression of the application, particularly in terms of visual presentation and general appeal. The Perspicuity (mean 1.670; variance 1.11) and Efficiency (mean 1.652; variance 1.00) dimensions are also categorized as “Above Average,” reflecting that the application is perceived as understandable, structured, and efficient in facilitating user interaction with minimal cognitive difficulty. These findings suggest that the pragmatic quality of the system has been implemented effectively.

However, the Dependability dimension (mean 1.589; variance 0.95), although still within a positive range, shows a relatively lower value compared to the primary pragmatic dimensions. This condition may be associated with technical aspects such as marker detection sensitivity, tracking stability, or limitations in user control flexibility during three-dimensional object interaction. Similarly, the Stimulation dimension (mean 1.545; variance 0.99) indicates moderate experiential engagement, suggesting that while the application functions adequately, the interactive experience remains predominantly informational and may benefit from the integration of more dynamic features to enhance intrinsic user motivation.

The Novelty dimension recorded the lowest mean score (1.205; variance 1.37). Although categorized as positive, this result reflects a comparatively limited perception of innovation. The reliance on marker-based AR technology and the absence of advanced interactive or gamified elements may contribute to this evaluation.

Overall, the benchmark comparison confirms that FOSSERA demonstrates strong pragmatic quality and positive overall appeal. Nevertheless, improvements in system responsiveness, interactivity, and technological innovation are recommended to strengthen hedonic quality dimensions, particularly Stimulation and Novelty. These

findings provide an empirical basis for further refinement of AR-based educational applications within the context of fossil learning media.

IV. CONCLUSION

This research has produced and assessed FOSSERA, an augmented reality-based application designed for the visualization of ancient human fossils. The development process followed the Multimedia Development Life Cycle (MDLC) framework, and the application was evaluated quantitatively through the User Experience Questionnaire (UEQ) with the participation of 28 respondents aged between 15 and 22 years. The evaluation outcomes indicate that FOSSERA received favorable user experience ratings on all six UEQ dimensions. Higher mean scores on Attractiveness, Perspicuity, and Efficiency demonstrate that the application is perceived as visually well structured, easy to comprehend, and effective to operate. These results confirm that the integration of augmented reality technology in FOSSERA contributes to a positive and satisfactory user experience.

Nevertheless, the Dependability, Stimulation, and Novelty dimensions recorded relatively lower mean values, indicating that several aspects still require improvement, particularly related to system stability, experiential engagement, and application novelty. A limitation of this study lies in the scope of the augmented reality content, which only represents the skull of ancient humans in 3D models and does not yet include a complete visualization of the entire skeletal structure. In addition, the relatively limited number of respondents may affect the generalizability of the findings. Therefore, future research is recommended to develop more comprehensive skeletal visualizations, increase the variety of learning objects, involve more diverse respondents, and apply additional evaluation methods to obtain a more comprehensive assessment of the application's quality.

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