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Original Article

Development of SIAR-SKULL: A Superimposed Augmented Reality Application for Enhanced Visualization in Skull Anatomy Education

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Abstract - *Although textbooks, 2D illustrations, and physical models have been the traditional means by which instructors and students learn human skull anatomy, these methods may limit a learner's ability to establish complex spatial relationships between different anatomical structures. Using Superimposed Augmented Reality (SIAR) is an alternative to traditional educational resources, allowing learners to visualize virtual anatomy in relation to the physical world. As a model for this study, a new Superimposed Augmented Reality (SIAR) application called SIAR_SKULL was developed to enable the learner to visualize three-dimensional skulls based on a photogrammetric model in real-time via markerless model-target tracking technology. An ADDIE (Analyze, Design, Develop, Implement, Evaluate) instructional design model was used to systematically analyze, design, develop, implement, and evaluate the application. In development testing, system functionality, stability, and cross-device compatibility were verified. The findings of this work establish both the technical feasibility of the suggested method and a validated platform for future empirical evaluations of usability and educational effectiveness.*

Keywords - *Enhanced Visualization, Education, Superimposed Technique, Augmented Reality, Skull.*

1. Introduction

Medical and allied health curricula place a large emphasis on anatomy education, and understanding the three-dimensional spatial relationships between anatomical structures within the body is a critical component of clinical practice. The human skull has many unique learning challenges as a result of its complex geometric shape, dense arrangement of foramina, interlocking sutures, and many important internal structures, all of which present barriers in understanding its anatomy. Many traditional teaching methods, such as textbooks, two-dimensional diagrams, plastic models, and cadaver dissection, still provide an acceptable means of learning anatomy; however, each of these approaches tends to poorly facilitate spatial cognition and long-term retention of learned material since learners generally mentally reconstruct three-dimensional structures from two-dimensional diagrams or static representations of three-dimensional structures [1]. Learned through research into advances in educational visualization, the use of interactive and spatially meaningful representation of abstract and complex structures significantly enhances how well learners engage cognitively with these materials and reduces unnecessary cognitive effort while helping to facilitate deeper understanding of science and medicine [2-4]. Specifically for anatomy education, interactive and dynamic visualizations improve learners' understanding of and ability to identify anatomical structures and how these structures communicate with each other, and subsequently, learners are able to apply their acquired knowledge in clinical settings [5]. In a number of different contexts, Augmented Reality (AR) has been found to be beneficial for visualising human anatomy. By combining actual real-world data with digital information, AR can provide a unique means of visualising anatomical structures. Current AR applications for anatomy use either marker-based tracking, screen overlaid images, or immersive virtual environments. Many of these systems have increased student engagement and satisfaction compared to traditional methods [6]. Evidence of improved objective learning outcomes compared to conventional learning methods has been mixed. Immersive AR systems and those employing marker-based AR have advantages over conventional anatomy education, but they also have some drawbacks. For example, AR systems generally have fewer actual 3-Dimensional (3D) rendering capabilities compared to regular teaching methods, and they can also have increased misalignment of the virtual anatomical models and corresponding 3D physical model of human tissue, printed marker requirements, and infrequently include tangible teaching materials as part of the learning experience.

In contrast, Superimposed Augmented Reality (SIAR) is the next generation of AR technology, where the 3D digital model is precisely positioned on top of the actual physical object. Such a system is capable of helping bridge the gap between 100% virtual rendering of anatomical structures and the need for students to be able to hold and feel the structures as part of their learning experience, while allowing for greater clarity of the virtual rendered anatomical model [7]. To date, the application of SIAR technology for education in skull anatomy has been largely unexplored, although it has great potential for both musculoskeletal and surgical education. A large number of AR systems that have been previously completed for viewing skull anatomy in 3D space have utilised a standalone visualisation of 3D models or utilising markers to overlay on real-world objects, but these systems do not often consider how well the visualisation matches the real object, how well layered anatomical labels are viewed, and how effective these systems are through a usability evaluation of the educational content being presented [8].

This absence creates an opportunity for an Anatomy-Focused SIAR application that can deliver to learners 3D skull models with accurate alignment to skull objects and, through an empirical study of the usability and functional performance of the system, provide evidence of the successful use of the application. Additionally, there has been little evidence from research studies that demonstrates the empirical success of the systems developed and implemented. Evidence of success is almost exclusively based on engagement measurements and has not included reporting on the testing of the system deployed or the reliability of the system across multiple devices. To fill this gap in the research literature, this study presents the development of SIAR-SKULL (Superimposed Augmented Reality), which is an Augmented Reality application designed to support skull anatomy learning through improved visualization and object-based interaction, by providing more accurately aligned object-based tracking of 3D skull models from photogrammetry with real skulls, while at the same time allowing students to view both internal and external anatomical structures in situ. The development of SIAR-SKULL follows the Instructional Design Model ADDIE, which provides a systematic approach to the analysis, design, development, implementation, and evaluation of the system.

This study provides three key contributions, all of which combine to contribute uniquely to this problem. The first contribution is the application of a markerless SIAR method on the skull (anatomy), which is likely one of the most complex and clinically important areas of research in terms of spatial complexity. Second, this research creates a new way to integrate photogrammetric-based 3D modelling with the use of actual objects (superimposing them over the digital 3D model), therefore improving not only the level of anatomical accuracy of the digital 3D model but also improving the alignment accuracy between a user and the virtual image within the AR application. Lastly, this research is the first to provide a systematic functional evaluation of three separate devices that are all based on the same application framework, creating the foundation for future studies evaluating the efficacy of the devices on learner performance and usability.

The structure of this paper is as follows: Section 2 reviews prior work in this area, focusing on visualisation and AR in anatomy education and specifically highlighting the inadequacies of current approaches. Section 3 will detail how to develop the SIAR-SKULL application, including the materials, framework, and methodology. Implementation and functional testing of the SIAR-SKULL application will be summarised in Section 4. In Section 5, the impact of this research on education is discussed along with a summary of its contributions and its limitations. Finally, section 6 will provide closing remarks and recommendations for future research.

2. Related works

Education has greatly benefited from utilizing visualization methods to help students learn by using visual information more effectively and understanding how different components relate to one another when learning about complex subjects. It is the brain's ability to naturally process the visual (and motion) elements found on dynamic visualizations that enhances comprehension [9]. Past studies have confirmed that visualization provides enormous help to students as they engage in inquiry-based Science, Technology, Engineering, and Math (STEM) education. Illustrating processes (like scientific processes) that are hidden or complex using a well-designed method of visualization allows students to understand them much more easily than if they were only learning about them using text or static images. Well-designed methods of visualization (like diagrams, charts, or animations) reduce the complexity of information, build students' understanding using the associated cognitive structure, and combine multiple representations into one centralized representation [10]. Visualization also allows learners to construct their own knowledge rather than just "read" or "see" it being presented to them. Furthermore, many studies have indicated that visual aids such as diagrams, drawings, and animations will enhance the effectiveness of a teacher when they are in line with the visual outlooks and understanding abilities of the students.

Many researchers have done studies that analyze how AR allows educators to provide immersive, engaging, and memorable learning experiences through the use of digital artifacts such as videos, pictures, and 3D models. Generally speaking, AR helps educate students about nonlinear and complex subjects, such as physics and chemistry, by providing them with immersive, interactive, and dimensional experiences. Among other examples, [6, 11-14] provide evidence that AR technology improves the ability to visualize and understand complex three-dimensional structures, such as the human body, in the anatomy curriculum. [15] Further support this with their augmented reality-based application for learning about anatomy. In their report, the authors discuss how AR provides educators and learners with a single, simple way to visualize complex anatomical relations and how AR-based education systems should consider issues related to visual accuracy, content organization, user interaction, and the level of engagement necessary to promote learning. Therefore, increasing understanding through the use of AR technologies will ultimately lead to increased confidence and appreciation for the subject matter.

[11] found that AR provides both tactile and visual stimulation for students when using anatomical models. Students can become fully immersed in the experience, making it possible for them to engage in greater depth when working with models of anatomical structures. The ability of AR to allow users to interact with three-dimensional models is particularly advantageous for students studying anatomical structures that are difficult to visualize (e.g., the skull).

[12] explored how AR technology could be used as an engaging interactive tool for the study of anatomy. Their research using the musculoskeletal system illustrated that AR-enhanced instructional methods enable learners to be engaged with materials more fully and retain information longer after receiving instruction. They also found that students demonstrated increased performance on post-test assessments after completing AR-enhanced lessons as compared to conventional methods.

[13] developed an AR technology system designed to provide personalized learning. They created a “magic mirror” AR system that provided users with real-time interactions with anatomical structures, including the skull. The results of these studies show that an increase in user engagement and an increase in the accuracy of virtually overlaid images in relation to the human body occurred because of this method of learning.

In addition to the two positive aspects about using AR, other studies have also shown mixed results when comparing AR to traditional methods of teaching to demonstrate the effectiveness of AR versus traditional methods [6]. A meta-analysis of the studies showed that while AR has not consistently provided students with a statistically significant increase in their anatomical test scores, the analysis shows that AR has a positive effect on a learner’s engagement and motivation to learn, which leads to increased learning after time has passed.

AR is not only being utilized in education but has also taken off in the surgical field. As noted by [14], AR can assist surgeons when performing complex surgical procedures by using virtual models of the anatomy of a patient. This approach of superimposing the virtual model on top of the actual structure provides the surgical community with an avenue for adapting and applying AR technology to anatomy education, particularly in the case of skull visualization, where accurate superimposition of the virtual model onto the skull is important.

The studies that have been reviewed thus far have all indicated that enhanced visualization has demonstrable advantages for learning anatomy and engaging learners, as well as enhancing learners’ ability to have a spatial understanding of the three-dimensional nature of anatomy. While previous studies have focused on AR visualization and marker-based AR applications, there is much less emphasis on superimposed AR, which allows virtual models of craniofacial anatomy to be placed directly over the actual skulls. Therefore, this represents a gap in the literature concerning the development and systematic evaluation of superimposed AR applications for craniofacial education, which serves as a primary motivation for this study.

3. Materials and Methods

To ensure the success of this study, a case study approach and a structured framework were utilized. This section outlines the specific case study selected for the project and details the framework employed in the development of the SIAR-Skull application in relation to the case study.

3.1. ADDIE-Based Research Design

The development of the SIAR-Skull application followed the ADDIE instructional design model, which consists of five phases: Analysis, Design, Development, Implementation, and Evaluation. The ADDIE model has been used for a systematic and organized process to validate and design the proposed superimposed augmented reality skull anatomy learning application.

3.1.1. The Analysis Phase

The analysis phase identified instructional and visualization issues related to learning skull anatomy. The analysis determined that learning skull anatomy via textbooks, 2D graphics, and traditional models tends to make it difficult for learners to see the details and spatial relations in complex skull anatomy. The visualization deficit is mainly due to the learner’s visual cognition and spatial memory ability to visualize complexity, rather than to the lack of instructional content. The conclusion of the analysis phase suggested that a technology-based visualization process is required for learning skull anatomy, rather than a pedagogical process, which is why a superimposed augmented reality process has been recommended.

3.1.2. The Design Phase

The design phase focused on planning the instructional content and system architecture and is analogous to the proposed framework in Section 3.3, which specifies the intended audience, the superimposed AR technique, the skull object, photographic 3D modelling, and the evaluation methodology.

Layered visualisation capability and object-based interaction were emphasised in the design of the system, as well as self-directed exploration. The design of the system is centred on how to provide functionality and support for the visualisation processes, rather than how to measure the learning results.

3.1.3. Development Phase

The SIAR-Skull application was developed in the Development Phase using Unity and Vuforia Engine. The primary components of this phase are the creation of the photogrammetric data of the three-dimensional skull model, training of model targets, and the addition of virtual labels to and interaction with the annotations. Sections 3.3.2 to 3.3.4 discuss the technical details of each of these aspects in detail.

3.1.4. Implementation Phase

The Implementation Phase focused on deploying the developed application onto a range of Android devices with differing hardware configurations. In this way, the project team has confirmed that the application will operate consistently and reliably on multiple platforms under realistic educational deployment requirements.

3.1.5. Evaluation Phase

The Evaluation Phase was composed of two levels: functional evaluation and usability evaluation. Functional evaluation is defined by the structured development testing processes conducted for this study in order to establish the stability and functionality of the platform and its content on multiple devices (see Section 3.3.5 and Section 4).

The Evaluation Phase also seeks to confirm tracking, visualization, and interaction functionality through the functionality assessments completed during the Evaluation Phase.

As such, while the evaluation framework is detailed in this paper, no empirical data on usability and learning effectiveness will be reported due to ethical and logistical constraints.

3.2. Case Study

Effective education in Skull anatomy is essential for students and professionals in the fields of medicine and allied health sciences. Normally, the key topics covered in Skull anatomy education are as follows:

- Basic Structure and Development: Includes skull divisions (neurocranium vs. viscerocranium), ossification processes, sutures, and fontanelles.
- Cranial Bones and Sutures: Identification and relationships of individual bones and major sutures.
- Cranial Fossae and Skull Base: Anatomy of anterior, middle, and posterior fossae, with key internal landmarks.
- Foramina and Canals: Locations and contents, especially related to cranial nerves and vessels.
- Cranial Nerves: Exit points and clinical significance of all twelve cranial nerves.
- Temporomandibular Joint (TMJ): Structure, muscles of mastication, and function.
- Paranasal Sinuses: Anatomy, drainage, and clinical relevance (e.g., sinusitis).
- Orbit and Eye Socket: Bony structures, muscle attachments, and neurovascular supply.
- Clinical and Imaging Correlation: Skull trauma, radiological landmarks, and surgical relevance.

The anatomy of the skull is complex in its three-dimensional structure and the relationships of the various parts; therefore, traditional teaching methods that generally use only textbooks and dissection from cadavers do not provide good opportunities for increasing students’ spatial understanding or creating long-term memory retention.

The purpose of this case study is to explore a recently developed superimposed augmented reality application that was used as a supplemental tool to aid in the teaching of the anatomy of the skull and create a basis for further development of augmented reality applications for anatomical education.

3.3. Framework

The framework proposed in this paper is based on the adaptation of Pradityatama, Dharma, and Arfian’s (2023) approaches to develop the SIAR-Skull application, as shown in Figure 1.

The proposed framework consists of five models, including User, Superimposed AR, Skull Object, Photogrammetric 3D Modeling technique, and System Usability Scale.

The proposed framework illustrates the complete design and evaluation structure of the SIAR-Skull application, including system development and planned usability assessment. In the present study, the framework is applied primarily to guide system design and functional validation.

Although usability evaluation using the System Usability Scale is incorporated into the framework, only development-level testing outcomes are reported in this paper. Empirical analysis of user learning performance and educational effectiveness is beyond the scope of the current study.

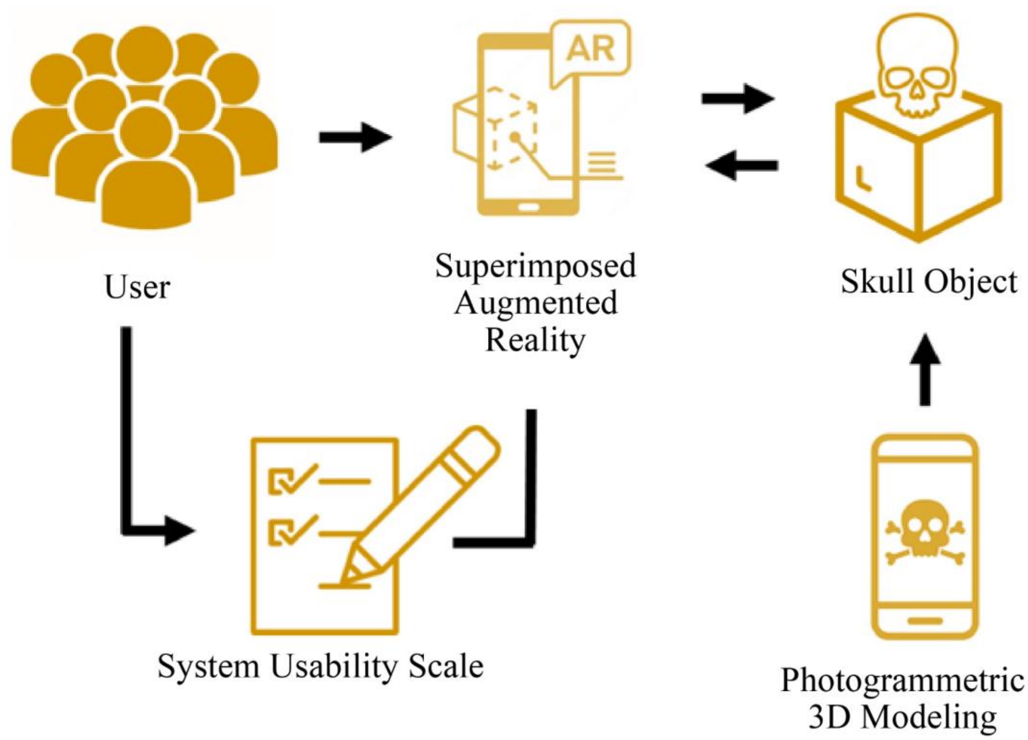

Fig. 1 Proposed framework of SIAR-SKULL

3.3.1. User

The target user is very important for fully utilizing the proposed application. This application is highly recommended for students and professionals in the fields of medicine, dentistry, and allied health sciences. Commonly, their environments provide the facilities or equipment regarding the human anatomy, especially the skull.

3.3.2. Superimposed Augmented Reality

Superimposed Augmented Reality (SIAR) is a type of augmented reality application that visually overlays digital content (3D models, text, images) as opposed to providing them in their physical environment; therefore, the user can experience their environment through an entirely different perspective. It enhances a user's perception of their environment by providing them with digital-contextual data that directly relates to what they are currently viewing.

SIAR utilizes a markerless technique in AR since there is no marker needed in the project. To develop SIAR, software like Vuforia Engine, Unity, and Vuforia SDK have been utilized.

Vuforia Engine-Model Target Generator is needed to train the 3D model of the Skull. The steps involved in this process are as follows:

- Creating Model Target
- Configuring Model Target
  - Selecting Model-up Vector: Up vector Y
  - Selecting Model Units: Meters
  - Selecting Model Coloring: Non-Realistic Appearance
  - Selecting Optimize Tracking: Default
  - Selecting Guide Views: Create an Advanced View to be tracked from all angles
  - Previewing Guide Views: full 360
- Generate Advanced Model Target
- Creating Training Session
- Creating Database
  - Selecting Model Targets
  - Start Train
- Export: Skull Package for Unity

To build the application, Unity and Vuforia SDK are required. The steps involved in this process are as follows:

- Installing Unity: 2022.3.40f1
- Importing Package Manager: Vuforia Engine AR
- Vuforia Configuration: Add app license key
- Scene Setup for Object Tracking
  - AR Camera: Vuforia Engine-AR Camera
  - Model Target: Vuforia Engine-Model Target
  - Importing Package: Trained Skull Package for Unity
  - Selecting Database and Model Target: Skull
  - Adding AR Content: Labels, Notes, etc
  - Guide View Mode: Guide View 3D
- Testing Scene from Unity Editor
- Building the application: APK

3.3.3. Sull Object

The skull object refers to the physical object of the skull as shown in Figure 2. The Skull object is a tangible replica model that serves as a real-world anchor for the digital (virtual) skull overlay. The Skull object acts as a tracking reference for SIAR. It allows precise alignment between real-world physical anatomy and the virtual overlay. By preparing the Skull object, it enhances the tactile learning, letting users touch and interact with a real object while seeing augmented data.

3.3.4. Photogrammetric 3D Modelling

The 3D Skull model has been developed based on a photogrammetric 3D modeling technique using Kiri Engine. Kiri Engine is a smartphone application that leverages photogrammetry to reconstruct real-world objects into digital models. The workflow, as shown in Figure 3, includes object preparation, image acquisition, cloud-based processing, reviewing process, and exporting process, resulting in a 3D asset suitable for use in the superimposed augmented reality application.

Fig. 2 Skull Object

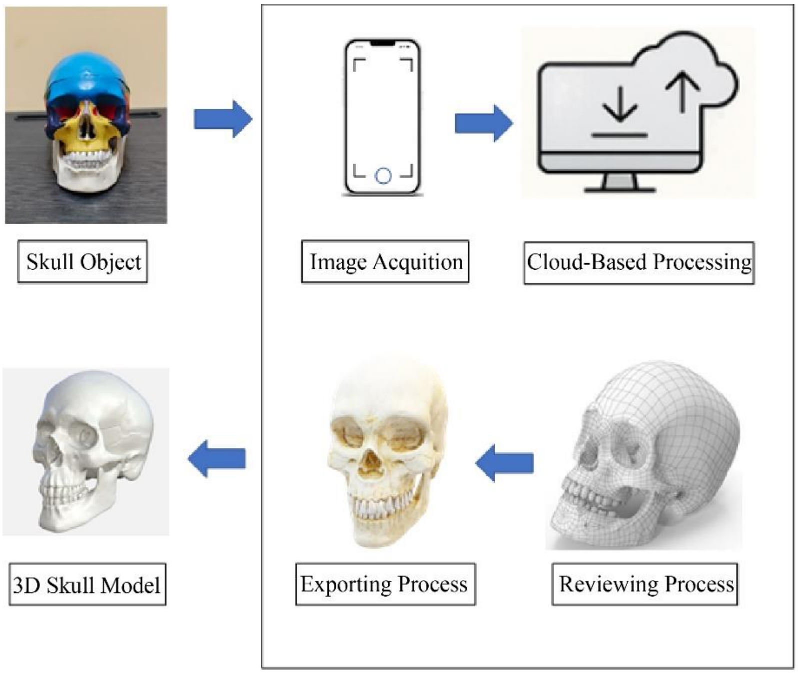

Fig. 3 The workflow of 3D skull model development

Object Preparation

In this case, the skull object has been prepared as an object on a desk. The quality of a photogrammetric model heavily depends on the texture, lighting, and environmental conditions during capture. The skull object should be opaque, non-reflective, and richly textured. Transparent or glossy surfaces may not yield accurate results. Furthermore, the surrounding environment should be evenly lit, preferably with diffused natural light, and contain a high-contrast, non-repetitive background to aid camera tracking.

Image Acquisition

A new project in the Kiri Engine application can be initiated by selecting either Photo Mode or Video Mode. Photo Mode allows for greater precision and control over image selection.

Users are advised to capture between 40 and 70 images encircling the object at various heights and angles, ensuring 60-80% image overlap and consistent object framing. The camera must remain at a fixed distance, and motion blur should be avoided. In this case, an Android smartphone camera has been utilized for taking pictures of the skull object.

Cloud-Based Processing

After taking pictures, the image dataset can be submitted to Kiri Engine's cloud servers. After submission, the photogrammetric algorithm reconstructs a 3D mesh for the skull and applies a texture map derived from the input images.

Reviewing Process

The resulting 3D skull model can be reviewed within the app, offering tools for basic mesh editing, cropping, and textural refinement. The desk has been removed by cropping the surface.

Exporting Process

Export options include widely supported formats such as .OBJ, .STL, .PLY, and .GLB/.gltf, enabling interoperability with software like Maya, Blender, Unity, and Unreal Engine. The generated assets are suitable for the superimposed augmented reality application.

3.3.5. Test

Tests can be divided into two categories, which are the development test and the implementation test.

- In the development test, the developed SIAR-Skull application will be evaluated on the functionalities of the modules designed in the proposed framework on three different devices. This test can be divided into platform and content functionalities. This paper discusses in detail the development test.

- Meanwhile, the implementation test utilizes the System Usability Scale (SUS) to test the proposed SIAR-Skull application among the users. This implementation test will be implemented after the development test results are satisfactory. After experiencing the application, the users are required to answer SUS in the form of a questionnaire. SUS has been adapted from the work of Menna Elshahawy, Safa Magdy, and Nada Sharaf (2023) in enhancing tourism through the application of ARTour.

The term "SUS" typically denotes the System Usability Scale, a popular survey instrument utilised to evaluate a system's or product's perceived usability. Since its creation by John Brooke in 1986, it has grown to be a common instrument in the study of User Experience (UX) and Human-Computer Interface (HCI).

Respondents score their degree of agreement with each of the ten statements in the SUS questionnaire on a range from strongly disagree to strongly agree. After that, the scores are computed to yield a numerical assessment of the system's usability, which aids researchers and designers in gauging user satisfaction and pinpointing areas in need of development. In SUS for SIAR-Skull, two types of questions have been developed, which are the engagement level test and usability test.

Type#1: Engagement Level Test questions:

- I felt in control of what I was doing
- I was absorbed intensely by the activity
- I found the activities enjoyable
- I thought about other things
- I found the activities interesting
- I was frustrated by what I was doing
- The activities bored me
- I was aware of distractions
- The activities excited my curiosity
- I knew the right thing to do
- It required a lot of effort for me to concentrate on the activities.

Type#2: Usability Test questions:

- I felt in control of what I was doing
- I think that I would like to use this system frequently.
- I found the system unnecessarily complex.
- I thought the system was easy to use.
- I think that I would need the support of a technical person to be able to use this system.
- I found the various functions in this system were well integrated.
- I thought there was too much inconsistency in this system.
- I would imagine that most people would learn to use this system very quickly.
- I found the system very cumbersome to use.
- I felt very confident using the system.
- I needed to learn a lot of things before I could get going with this system.

Both testing categories are essential to ensure that the SIAR-Skull application operates reliably and meets usability requirements.

However, due to procedural constraints, ethical approval considerations, and study scope, this paper reports only the results of development testing. No statistical analysis of learning performance or user engagement outcomes is presented.

4. Result

The SIAR-Skull application was developed and implemented as a functional prototype for end-users. Comprehensive testing was conducted to evaluate the application's full range of functionalities and overall reliability.

This section provides a detailed discussion of the deployment and configuration process, the user interface design, and the testing procedures carried out.

4.1. Deployment and Configuration

SIAR-Skull has been developed as a mobile Android application using Unity 3D, Vuforia SDK, and Vuforia Engine.

In terms of hardware, this application has utilized a computer of Lenovo Legion Y520 i7 with Intel® Core™ i7-7700HQ CPU@2.80Ghz processor, Nvidia Geforce GTX1050 graphic card, 12 GB RAM, SSD 240 GB hard disk, and Windows 11 platform.

Meanwhile, for the implementation, Honor X9c with Android Version 15, Oppo F11 Pro, and Vivo Y11 with Android Version 11 have been installed with the application to test running on the mobile phones. For the Skull object, it is a 1:1 scale, colorful human adult with Brain Stem Anatomy Medical Teaching Model.

This Skull is made of PVC material with 21cm x 15cm x 19cm in size. It can be disassembled into 3 parts, which are Calvaria, Base of Skull, and Mandible.

4.2. Interfaces

The outputs of the proposed framework can be seen in the form of interfaces. SIAR-Skull has 9 main pages in the application.

Fig. 4 Start page

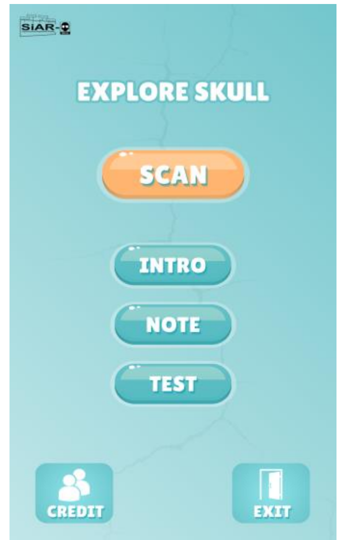

Fig. 5 Main menu page

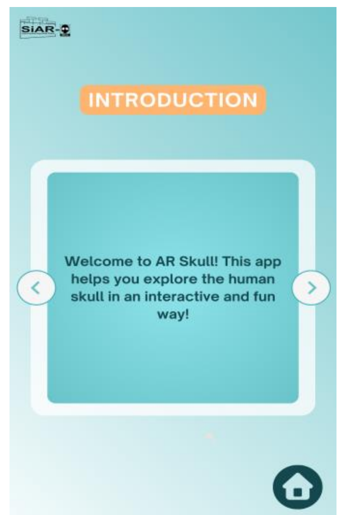

Fig. 6 Introduction page

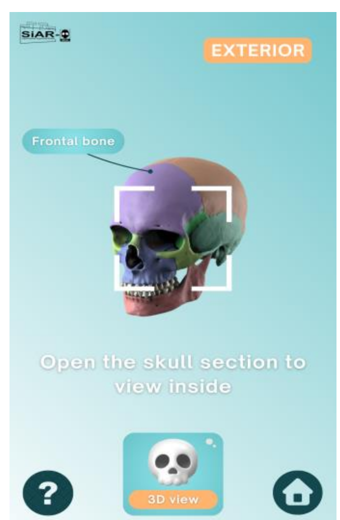

Fig. 7 Scan page

Fig. 8 Exterior scan page

Fig. 9 Interior scan page

Fig. 10 Instruction page

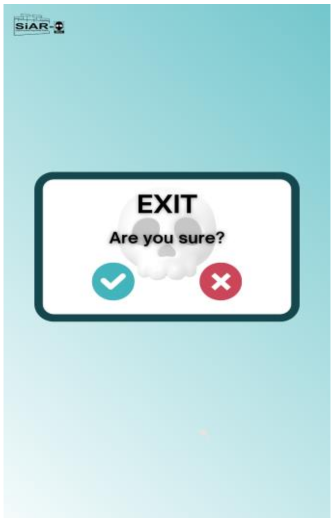

Fig. 11 Exit page

As shown in Figure 4, the Start page is a landing page in the application. It has only one button, which is the Start button. When the user clicks the Start button in the Start page, the Main Menu page will be opened as shown in Figure 5. This page contains buttons for Scan, Intro, Note, Test, Credit, and Exit.

As shown in Figure 6, the user will be directed to the Introduction page when the Intro button is clicked. This page contains a welcome message to the user. The user can go back to the Main Menu page by clicking the Home button. When the user clicks the Scan button in the Main Menu page, the user will be redirected to the Scan page.

As shown in Figure 7, the Scan page has two sub-pages, which are the Exterior page (See Figure 8) and the Interior page (See Figure 9). This page will open the smartphone camera for tracking the skull object. When the Skull object is tracked, the virtual labels and notes will be displayed. Besides, this page contains Instructions and Home buttons. The Instruction page will be open when the user clicks the Instruction button.

As shown in Figure 10, this page contains the guidelines to use the application of SIAR-Skull especially for scanning the Skull object. The Exit page as shown in Figure 11, will be open when the user clicks the Exit button. This page will display the confirmation message to leave the application of SIAR-Skull.

4.3. Testing

In this paper, the development test has been implemented to evaluate the functionalities of the modules designed in the proposed framework in three different devices, as shown in Table 1. The testing called test case could be divided into Test Case 1 for the platform functionalities and Test Case 2 for the contents functionalities, as shown in Tables 2 and 3.

Table 1. Device types for the implementation of the development test

	Device#1	Device#2	Device#3
Device Name	Honor X9c	Oppo F11 Pro	Vivo 1906
Android Version	15	11	11
Processor	Snapdragon 6 Gen	Octa-core	1.95 Snapdragon 439 Octa-core
RAM	12.00 GB	6.00 GB	3.00 GB
Storage	512GB	128 GB	2 GB

Table 2. Test case 1 for the SIAR-Skull platform functionalitics

Page	Procedures	Expectation	Results		
			Device#1	Device#2	Device#3
Start page	Loading in the Start page Click on the Start button.	Display name and logo of SIAR-Skull. Go to the Main Menu page.	Success Success	Success Success	Success Success
Main Menu page	Click on the Scan button. Click on the Intro button. Click on the Note button. Click on the Test button. Click on the Credit button. Click on the Exit button.	Go to the Scan page. Go to the Introduction page. Go to the Note page. Go to the Test page. Go to the Credit page. Go to the Exit page.	Success Success Success Success Success Success	Success Success Success Success Success Success	Success Success Success Success Success Success
Introduction page	Loading in the Introduction page Click on the Home button.	Display a welcome message. Go to the Main Menu page.	Success Success	Success Success	Success Success
Scan page	Loading in the Scan page. Click on the Exterior button. Click on the Interior button. Click on the Instruction button. Click on the Home button.	Display an instruction to click either Interior or Exterior categories. Go to the Exterior page. Go to the Interior. Go to the Instruction page. Go to the Main Menu page.	Success Success Success Success Success	Success Success Success Success Success	Success Success Success Success Success
Interior Scan page	Loading in the Interior Scan page. Click on the Instruction button. Click on the Home button.	Open the smartphone camera. Go to the Instruction page. Go to the Main Menu page.	Success Success Success	Success Success Success	Success Success Success
Exit page	Loading in the Exit page.	Display the confirmation message.	Success	Success	Success

Table 3. Test Case 2 for the SIAR-Skull Contents Functionalities

Page	Procedures	Expectation	Results		
			Device#1	Device#1	Device#1
Start page	Loading in the Start page.	Display name and logo of SIAR-Skull.	Success	Success	Success
Main Menu page	Loading in the Main Menu page.	Display Scan, Intro, Note, Test, Credit and Exit buttons.	Success	Success	Success
Introduction page	Loading in the Introduction page.	Display a welcome message.	Success	Success	Success
Instruction page	Loading in the Instruction page.	Display a video of the tutorial.	Success	Success	Success
Scan page	Loading in the Scan page.	Display an instruction to click either Interior or Exterior categories.	Success	Success	Success
Exterior Scan page	Loading in the Exterior Scan page. Camera detects the Exterior Skull Object. Camera displays the virtual guideline of the Skull.	Open the smartphone camera. Display the virtual guideline of the Skull. Display the virtual labels of the External Skull.	Success Success Success	Success Success Success	Success Success Success

	Camera displays the virtual labels of the External Skull.	The virtual labels can be clicked and loaded to the related pages.	Success	Success	Success
Interior Scan page	Loading in the Interior Scan page.	Open the smartphone camera.	Success	Success	Success

As shown in Table 2, there were several buttons placed on each page in the SIAR-Skull application. The users would be brought to certain pages when the buttons were clicked. The functionalities of each button in this test case were successful for the three different devices installed. Table 3 describes the test case of content functionalities in the SIAR-Skull application implemented on the three different devices. The content functionalities included the capabilities to display instructions, to detect the Skull object, to display the labels, to click the virtual buttons of the labels, and to load the related pages upon the clicks of virtual buttons, as shown in Figure 12. For this test case, the results from the three different devices show that the functionalities of the SIAR-Skull contents had been achieved successfully.

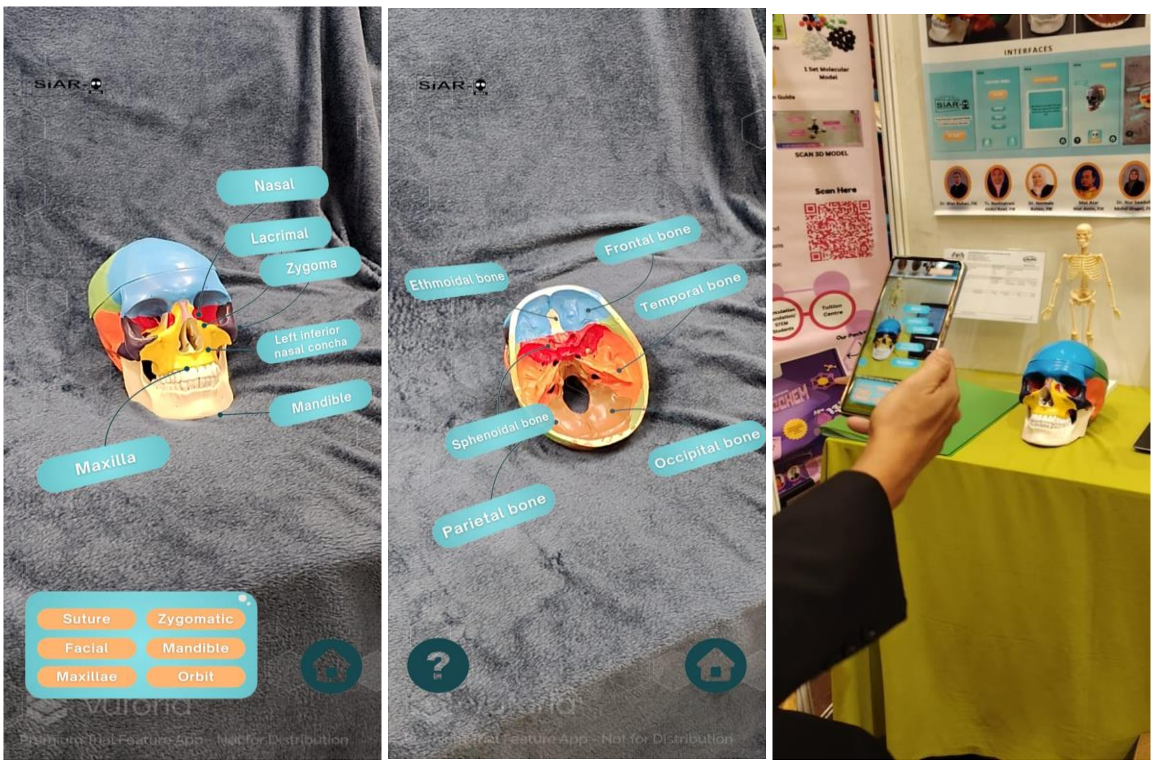

Fig. 12 The success of detecting the Skull and displaying labels for Exterior and Interior Skull

SIAR-Skull app passing all of the required tests or platform and content test cases on all types of devices indicates that it has developed a consistently accurate object recognition function, is able to properly align images of skulls in their three-dimensional position, as well as maintain the quality and accuracy of user interactions.

The reliability of the functional capability of the system is the most important factor in determining whether it can be used in an educational environment, as errors in tracking and visualization lead to compromised anatomical interpretation. Thus, the results indicate that the proposed system is technically feasible and passes the baseline requirements for actual instructional use in an educational context, thus qualifying for pedagogical evaluation.

5. Discussion

The development and implementation of the SIAR-Skull application demonstrate how superimposing augmented reality allows one to view skull anatomy in more detail through a consistent and reliable application of technology. In contrast to the traditional methods of teaching through the use of still images or physical skull models, SIAR-Skull allows for the ability to view the skull anatomy dynamically and in three dimensions. These capabilities were made possible by allowing real-time positioning of a physical skull model in relation to digital annotations placed over the skull model. The primary contribution of SIAR-Skull lies in its integration of photogrammetric three-dimensional modeling with markerless superimposed AR tracking. The system allows users to see anatomical labels and structures on a physical skull model, thus maintaining the three-dimensional relationship between the virtual content and the skull. This design allows an accurate representation of important bone features, such as sutures, foramina, and cranial fossae that are not identified on a physical model and do not require external tracking devices.

SIAR-Skull provides layered visualization and interaction capabilities. Therefore, SIAR-Skull provides a user-friendly interface for presenting content. The design features related to learner engagement from previous research on user interaction, but there is no measurement by this research of the learning outcomes and motivation of users who use the application. Thus, the educational benefits only come from what the design can support rather than from verified empirical results of the educational benefits.

Development test results have demonstrated that SIAR-Skull works well across Android devices, allowing for the possibility to scale up its use to educational contexts. This information has demonstrated that we have developed an application that is stable enough to support future studies to do a controlled evaluation of usability, effectiveness in education, and the ability to compare with existing approaches to education.

6. Conclusion

The article describes the design and development of SIAR-Skull, which is an AR application for visualization of cranial anatomy using augmented reality augmented by 3D model reconstruction. In addition, this article has demonstrated through the use of photogrammetry and markerless AR tracking that it is technically feasible to achieve accurate real-time superimposition of a virtual skull onto an actual skull.

Testing at the development level has also shown that the developed application works very well under several different mobile platforms and offers stable visualization and interaction capabilities. Although the framework has included tools to evaluate usability, the current study does not include an actual empirical evaluation of either the effectiveness of learning or the user experience.

The results of the current study confirm that SIAR-Skull offers a validated technical framework for the visualization of anatomy and lays the groundwork for future studies. Future research will include pilot studies, statistical analysis to determine usability and learning outcomes, and comparison with existing tools for anatomy education in order to determine their respective educational effects.

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