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Short Paper

CardioCoLab: Collaborative Learning of Embryonic Heart Anatomy in Mixed Reality

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Abstract

The complexity of embryonic heart development presents significant challenges for medical education, particularly in illustrating dynamic morphological changes over short time periods. Traditional teaching methods, such as 2D textbook illustrations and static models, are often insufficient for conveying these intricate processes. To address this gap, we developed a multi-user Mixed Reality (MR) system designed to enhance collaborative learning and interaction with virtual heart models. Building on previous research, we identified the needs of both students and teachers, implementing various interaction and visualization features iteratively. An evaluation with teachers and students (N = 12) demonstrated the system's effectiveness in improving engagement and understanding of embryonic heart development. The study highlights the potential of MR in medical seminar settings as a valuable addition to medical education by enhancing traditional learning methods.

CCS Concepts

• ***Applied computing*** → ***Interactive learning environments;*** • ***Human-centered computing*** → ***Mixed / augmented reality;***

1. Introduction

Understanding the morphology and function of organ systems, as well as the spatial relationships of anatomical structures is essential in early medical studies [PSH21]. Traditionally, anatomical knowledge is imparted through lectures, seminars, and the dissection of body donors, with the latter providing practical experience and a better understanding of spatial relationships [PS18]. Due to the limited availability of specimens, students must rely on static illustrations and models. Digital approaches have been introduced and students now have access to online videos, workshops, and learning apps [PACR22]. Augmented, virtual, and mixed reality (AR/VR/MR) applications are also increasingly being integrated into medical education, as they offer significant benefits such as immersive simulations, repeatable practice, and minimal ethical concerns for medical training [Gar21, TCK*22]. These technologies effectively address the shortcomings of traditional methods in understanding complex spatial relationships [HMEW21], showing positive trends in learner engagement and performance [TVLVA*24]. However, their implementation remains complex, requiring careful consideration of learner and teacher needs [SPSM21]. Various learning formats are documented, highlighting the growing recognition of the benefits of collaborative learning environments. MR technologies have shown potential in enhancing clinical skills and 3D anatomical understanding through various collaborative platforms [PKS24, BLE*21, SSS*21, MKY*24].

While previous studies have primarily focused on adult anatomy, our work shifts the focus to early development. Embryology is fundamental to understanding the form and function of anatomical structures and congenital diseases. The rapid and simultaneous growth processes occurring within a short time frame, combined with the lack of 3D orientation, make it challenging to grasp [Pat20]. The heart, in particular, undergoes multiple complex morphological changes that are essential to understand for diagnosing and treating congenital heart defects. Traditional learning tools, such as 2D representations in textbooks, videos, or static 3D models, are limited in capturing these dynamic processes [CKdB20, AHKM22]. Multimedia content is increasingly used to illustrate developmental stages [aMP10]. While interactive 3D models and mobile applications have shown promise in enhancing student understanding of embryonic development, they often lack smooth performance, comprehensive stage transitions, and sufficient interactivity to capture the complexity of morphological changes [dBdJH*12, HSS*21, GSHL22, TPC20].

We addressed this issue in our previous research, where we presented a VR learning environment for individual exploration, enabling students to interact with embryonic heart models to better understand its development [SKW*23]. Building on this foundation, we expanded the content and explored a collaborative approach. In an expert workshop, we developed a multi-user MR-based system to assess didactic strategies [SKM*24]. Following an iterative design process, we incorporated feedback and selected the

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most promising visualization methods and interaction modalities to further enhance the system. In this paper, we introduce an updated MR-based system and present its application in a use case. A user study involving students and moderators (N = 12) simulated a seminar setting to evaluate the system's pedagogical suitability.

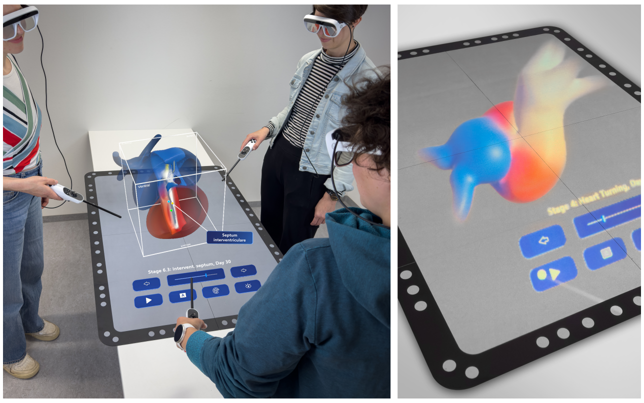

Figure 1: *Left: Photomontage of the system, showcasing users interacting with the interface from the moderator's perspective, including all control elements and overlay information (orientation grid, labels). Right: Photograph captured through the AR glasses.*

2. System Design & Implementation

In our VR application, students were allowed to familiarize themselves with each developmental stage step-by-step at their own pace in a closed, distraction-free environment [SKW*23]. Using hand interaction to manipulate virtual heart models, students can trace morphological transitions and examine specific aspects of dynamic heart formation and orientation in detail.

2.1. Original System

Building on the VR system, we developed an MR-based multi-user platform (hereinafter referred to as *original system*) with a different didactic approach designed to integrate the social aspects of learning, promoting knowledge exchange and collaboration while addressing the needs of both students and teachers [SKM*24]. We implemented this concept using the Tilt Five game board system (Tilt Five, Inc., USA), which features infrared cameras for positional tracking and lightweight glasses equipped with dual projectors that project AR overlays onto a retroreflective panel. On the software side, we used Unity (Unity Software Inc., USA) running on Microsoft Windows, in conjunction with the Mixed Reality Toolkit 3 (Microsoft Corp., USA), which we utilized to design the user interface (UI). For the teacher, we implemented advanced touchless interaction to manipulate the virtual models and interact with a dedicated UI using Ultraleap's Stereo IR 170 Evaluation Kit (Ultraleap Ltd., USA), mounted on a custom headstrap. 3D models were created using MudBun (longbunnylabs), a tool that utilizes signed distance fields for real-time procedural volumetric mesh generation in Unity. The marching cubes algorithm was chosen to polygonize the 3D scalar field, ensuring high performance through the use of spatial hashing and sparse voxel trees. The new hardware necessitated a completely redesigned UI, enabling two user roles with different control capabilities. The setup allows one user, referred to as the moderator (e.g., the teacher), to lead the seminar session while up to three users (students) participate. Each user has controller inputs to manipulate the 3D models, allowing for rotation and annotating the model with a raycast beam. Each student and the moderator were assigned a unique color, allowing them to draw on the model. The moderator is equipped with advanced functions, including toggling information labels (designation of the respective anatomical structure) placed flat on the ground next to the model, enforcing model alignment views (forced moderator's perspective), and disabling the beam. Additionally, the moderator can navigate through each stage, play and stop the heart animation using a button, or manipulate the animation with a slider. The moderator can additionally deform the model through hand interactions and control the animations. In the course developing the *original system*, we expanded the content of the VR system by introducing additional developmental stages, now covering days 18 to 37 of embryonic heart development. This expansion includes visualizations of the internal structures. We evaluated different configurations of gameboard´s placement and the integration possibilities and challenges in the medical curriculum during a workshop with anatomy experts.

2.2. Updated System

Based on issues identified during interviews with experts, we identified the most promising improvements to further develop the *updated system* used in this article. This includes enhancing existing features and improve functionality. The evaluation of the *original system* revealed that placing the game board flat on the table is the most suitable configuration. This setup offers optimal visibility and interaction opportunities for multiple users, which is why we adopted it in the *updated system*. On the software side, the *updated system's* fundamental structure remained unchanged as described in the publication of the *original system* [SKM*24]. Due to performance issues observed during the expert evaluation, which arose from the complexity of visualizing and animating the internal structures, we opted for a collection of individual meshes to be loaded sequentially. This approach resulted in a smooth animation compiled from approximately 200 exported meshes of each 3D model. Unlike the *original system*, we opted for controller input for all users. While hand interaction is ideal for understanding shape changes, we observed that having multiple people around the game board often leads to obstructions and visibility issues. Additionally, there were tracking problems due to the distance between users and the play area, making distance interactions difficult. A new feature, previously overlooked in the *original system*, is the ability to scale the model, using the controller. If the model is scaled too large and extends beyond the edges of the game board, frame cancellation can occur—a phenomenon where a virtual object is cut off by the screen edges when it appears in negative parallax. To counteract this, we implemented alpha blending using custom shaders to fade the edges (see Figure 1, right). Due to the transition to individual meshes for the 3D models, the inactive painting (annotation) feature had to be omitted in the *updated system*, as discrepancies would arise when switching between models. Experts also noted that a better differentiation between individual users would be beneficial, and that there is a possibility of the colors of the structures being overwritten during painting. For this reason, we implemented a continuous, directed beam from the controller, which creates a cursor at the intersection point when it hits the surface of the mesh. When activated by the moderator interface, dynamic labels with the respective medical descriptions of the cardiac structures appear. These labels are aligned in the user's view and positioned to the left or right of the 3D model depending on their location. The cursors are numbered for each user, facilitating communication and user identification. The three basic interactions—rotating, scaling, and cursor—are equally accessible to all users. The operating elements for the moderator remained the same, with the addition of consistent icons designed for the functions. Toggling the annotations now also causes a white orientation frame with medical position labels to appear, along with the name and timeframe of the current phase. Another feature, developed primarily for our study, allows example questions and answers related to the system's content to be displayed using two buttons on the controller. This functionality is intended to assist the moderator during the session. In the final development stages, the heart model is cut open to visualize internal processes. The model consists of a fixed mesh representing half of the heart, with the animation added as a separate object, aligned to overlap with the heart mesh. Since the heart mesh obscures parts of the animation, it becomes transparent during animation playback, allowing a clear view of the internal processes from all angles (see Figure 1, left).

3. Evaluation

A user study was conducted to evaluate usability, gaming experience, immersion, and technology acceptance across different user groups to gain insights into the integration of such systems into anatomy education. We aimed to assess the perspectives of the moderator and the students. Four sessions were conducted, with three participants in each session: one serving as the moderator and two as students. The reduced number of student users was intended to stabilize the system's performance. Moderators were required to exhibit teaching experience in the broad medical context. Three male and one female moderator were recruited. Their mean age was 27.75 years, and they had, on average, 3.38 years of teaching experience. Additionally, eight medical students were recruited, seven of whom were female. Their average age was 25.83 years. In each session, a seminar was simulated with a moderator guiding two students. The study lasted 60 to 90 minutes for the students, while the moderators were asked to arrive 30 minutes earlier for preparation and briefing. During this preparation time, informed consent and demographic information were collected, and the moderators were trained on how to use the application. Prior to the study, the moderators received potential questions, developed in collaboration with experts in anatomy education, which covered the scope of the application. This included one or two questions per developmental stage designed to stimulate discussion, though they were not mandatory. While the moderators were encouraged to familiarize themselves with the topic, the questions and answers were available in printed form and could be accessed virtually during the session. After the students had arrived, we also gathered their informed consent and mandatory study documentation. and the introduction by the study instructor began. The moderator independently introduced the application and explained the procedure. Once the AR glasses were on, a 3D model of the controller was shown to illustrate its functions. When everyone was ready, the content phase began, guiding through the different stages of heart development. The moderator ensured that lively communication was maintained within the group.

At the end of the seminar, all participants completed several questionnaires. We assessed the usability using the System Usability Scale (*SUS*). We were further interested in how immersed the users were in the MR environment, measured using the AR Immersion Questionnaire (*ARI*). Since the type of MR learning platform was very new to our participants, the Technology Acceptance Model (*TAM*) was employed to assess *perceived usefulness* (*PU*) and *perceived ease of use* (*PEU*) as key determinants of users' attitudes and behavioral intentions. In addition, the core, social presence, and post-game components of the Game Experience Questionnaire (*GEQ*) were used to evaluate the overall experience of the application. Finally, the experiment concluded with an open discussion and interview, collecting qualitative feedback on the MR prototype's interaction and visualization schemes, as well as the learning platform's feasibility as a potential part of the curriculum.

4. Results

4.1. Quantitative Measures

Results of the ARI questionnaire show that both study groups perceived a comparable (medium high) degree of immersion using our MR application (Mod: $M = 5.11, SD = 0.66$; Stud: $M = 4.80, SD = 0.85$; also see Figure 2a). This finding was expected since immersion is more influenced by technical factors of the used hardware, which was identical in both groups. Our prototype received promising usability ratings from both user groups. Moderators gave slightly lower SUS scores ($M = 76.25, SD = 9.24$) than students ($M = 83.13, SD = 6.51$), yet both values are above generally acknowledged thresholds for good to excellent usability (see Figure 2b). These findings are also reflected by the TAM assessments (see Figure 2c). Lower scores indicate better perceived usefulness and ease of use. For both metrics, the student group assessed the application as better (PU: $M = 24.65, SD = 16.43$; PEU: $M = 32.29, SD = 15.99$) than the moderator group did (PU: $M = 24.65, SD = 16.43$; PEU: $M = 32.29, SD = 15.99$). Overall, good scores were achieved, however the only mediocre ease of use rating of moderator role indicates room for improvement. A full overview of all GEQ sub-scales can be seen in Figure 3 and Figure 4. Notably findings include a higher sense of flow reported by moderators ($M = 2.20, SD = 0.94$; Stud: $M = 1.74, SD = 1.02$), indicating they were more engaged than students while running the seminar. Moreover, students only reported a small degree of challenge ($M = 0.78, SD = 0.25$), while moderators perceived the seminar as considerably more challenging ($M = 1.80, SD = 0.67$). Negative affect, i.e., negative emotions towards the application, were rated low by both groups (Mod: $M = 0.50, SD = 0.54$; Stud: $M = 0.59, SD = 0.97$), while positive affect, i.e., positive emotions towards the application, were assessed similarly high (Mod: $M = 2.80, SD = 0.71$; Stud: $M = 2.90, SD = 0.96$). Regarding the social presence component, it is most noteworthy that behavioral

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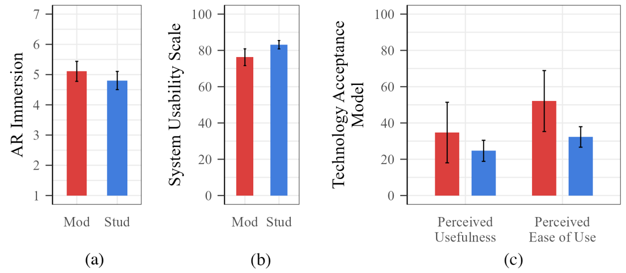

Figure 2: *ARI (A), SUS (b) and TAM (c) ratings of the ■ Moderator ■ Student groups. Mean values and standard error bars.*

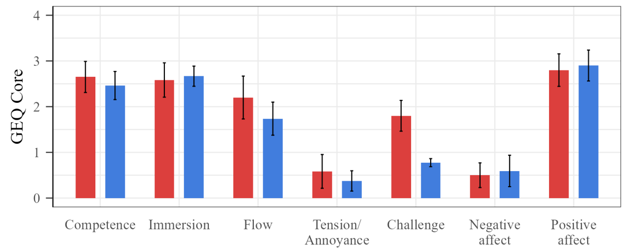

Figure 3: *GEQ core module ratings of the ■ Moderator and the ■ Student groups. Mean values and standard error bars.*

involvement, i.e., the amount influence of users on each other's actions, was perceived higher by moderators ($M = 2.75, SD = 0.50$) than by students ($M = 1.50, SD = 0.77$). This suggests that the teaching functionalities provided to the moderator fulfilled their purpose in the way that the moderator perceived their actions had an effect on the students. The post-game GEQ component suggests that both groups had little issue to transition out of MR back to real life (Mod: $M = 0.67, SD = 0.72$; Stud: $M = 0.38, SD = 0.33$), that the application was not tiring (Mod: $M = 0.63, SD = 0.95$; Stud: $M = 0.38, SD = 0.88$), and that positive experiences (Mod: $M = 1.63, SD = 0.79$; Stud: $M = 1.67, SD = 0.81$) overshadowed negative ones (Mod: $M = 0.54, SD = 0.64$; Stud: $M = 0.25, SD = 0.41$).

4.2. Qualitative Feedback

During the interview phase, participants rated the animated 3D visualization of the embryonic heart as an improvement over conventional 2D cross-sections in textbooks. In particular, the last stages of the application, in which changes inside the heart are visualized by a halved heart model shown transparently, were found to be helpful. However, participants expressed a desire for this transparency to be maintained even when the animation is not being played. Additionally, several participants noted that visualizing more complex information on the heart model, such as rendering blood flow, would be beneficial. Regarding interaction, all participants found the system easy to use and to learn. The interaction options, especially their variety, were positively assessed by participants. They found the number of interaction options to be sufficient, allowing them to engage with the heart visualization effectively without being overwhelmed by excessive choices. Occasionally, problems with correctly aligning the heart model were reported.

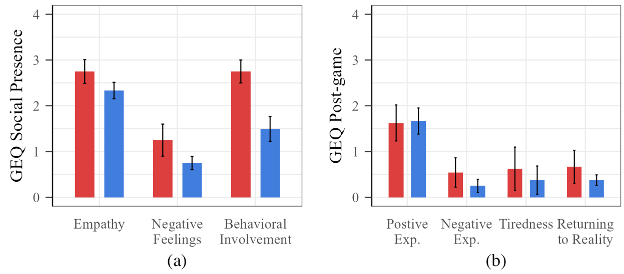

Figure 4: *GEQ social presence (a) and post-game (b) module ratings of the ■ Moderator and the ■ Student groups. Mean values and standard error bars.*

However, this could be mitigated by changing the head position and thus the perspective. The MR hardware was generally rated positively. However, the glasses were noted to be uncomfortable on the ears and got warm in the forehead area. Some participants also perceived the resolution as too low to properly read text. With respect to using the prototype as a learning environment, participants assessed the system as useful for anatomical training. In particular, the participants could imagine the MR system as an extension, or even as a replacement, for the dissection course. However, some issues regarding group size were identified, including limited space around the area of interest and visual clutter resulting from multiple interaction markers on the model.

5. Discussion & Conclusion

Data across quantitative questionnaires suggests that using our MR prototype is positively perceived by moderators and students alike. High levels of competence, flow, immersion, and positive feelings are accompanied by low levels of tension, challenge, and negative feelings. Together with favorable technology acceptance model scores, this implies that the application is well accepted, which in turn increases the chance of learning success. Participants of the student group assessed the usability, usefulness, and ease of use of our application as better than the moderators did. This finding is probably due to the reduced amount of interaction possibilities of the students. The moderators needed to control the whole interface while holding their seminars. This additional workload may have dampened their overall assessment of the MR environment. This is also in line with their notably higher challenge rating of GEQ core questionnaire. The qualitative feedback from the participants also supports the result of the positively perceived application but also highlights some limitations and requires further development. For instance, additional visualization contents like blood flow were desired and challenges due to large group sizes were identified. More conventional seminars, like preparation courses, often involve more students than the suggested hardware can provide. Using our proposed system, a seminar setting in small groups is thus recommended. Extending the number of possible users would, however, expand the potential of our MR learning platform. Our study was limited by a comparably low sample size. For this reason, no further statistical analyses were conducted. Data from more participants should be collected in future work to obtain more meaningful results and feedback. This is especially true for the moderator group, which consisted of only four participants. Future recruitment should also consider a more diverse gender distribution of the sample, as the current sample may be somewhat biased in this regard. In preparation for the simulated seminar, we encouraged the moderator to maintain consistent communication within the group. The provided example tasks and questions were followed to varying degrees. We were surprised by the individual ways they were utilized. In addition to directly querying knowledge, open questions were posed to the group, and individuals were also addressed directly. Thanks to the teaching experience of the moderators, they could respond individually to situations and questions. Due to this alternating approach, the opportunities for interaction, and the ability to toggle various information and visualizations, not every developmental step was presented in the same manner. We observed a lively atmosphere, likely due to the small group size, which ensured that everyone had the opportunity to participate. Overall, it can be concluded that our MR prototype is a suitable addition to use in anatomy seminars. Our system provides a positive and helpful user experience and offers great learning and teaching potential. However, some further development steps are required to achieve its full potential.

Acknowledgments

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