Augmented Reality aided learning of human embryo anatomy: A study on motivation and usability

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Abstract

Modern advances in augmented reality technology make for promising new uses in education. A discipline that can possibly benefit from augmented reality learning experiences is human embryology. Insight into human embryology is of considerable clinical interest, as it can explain congenital malformations that make up for 20% of all neonatal deaths. Conventional embryology teaching methods are however limited due to financial and ethical constraints, and a recent desktop computer application, that implements excellent recently published anatomy models, does not utilise the affordances offered by augmented reality. An augmented reality application, that displays these models, to aid embryology education is implemented and compared to the desktop computer application in controlled experiments that aim to measure motivation and usability. The augmented reality application was found to provide a significant increase in intrinsic motivation in the participants over the desktop computer application. Furthermore, the participants rated the augmented reality application as more valuable and useful to them. Little difference was found in usability between the applications, possibly due to the little prior experience with augmented reality applications. These results show benefits of augmented reality learning experiences over more traditional desktop computer simulations and great potential for future use in (embryology) education.
Acknowledgements

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Educational technology is transforming the way students engage and interact with learning materials, in an attempt to enhance the learning process. Augmented Reality is an increasingly popular visualisation technology with potential applications as educational technology. It can be used to make spatially complex three-dimensional data, that is hard to visualise properly in two dimensions, more comprehensible and accessible by providing an intuitive means of interaction with this data. Anatomy education is a field that can benefit from augmented reality, because of its many complex spatial relationships.

A group of researchers from the Academic Medical Centre recently published a 3D digital atlas of human embryology with anatomy models spanning the first two months of human development [1]. These models are made available in interactive 3D-PDF files (i.e. interactive three-dimensional computer models) and are designed to replace the increasingly schematic, and sometimes incorrect, two-dimensional schematics in conventional text-books on human development. These 3D-PDF files do however not utilise the advantages that augmented reality is theorised to offer [2]. Augmented reality can thus be an effective education method in this field.

There is an ongoing debate concerning the optimal methods of anatomy education [3]. This research aims to contribute to this debate by comparing the 3D-PDF interactive computer models with augmented reality as teaching methods of embryo anatomy. This is in line with the suggestion by Hackett and Proctor to focus on augmented reality aided anatomy education compared to alternative visualisation paradigms in future research [4]. Two hypotheses are researched:

- **It is hypothesised that augmented reality enhances the motivation of students in comparison to the interactive desktop computer models, as suggested in similar studies in this field** [5, 6].
- **It is hypothesised that the usability (i.e. effectiveness, efficiency and user satisfaction) of augmented reality is higher than that of the interactive desktop computer models.**

This research aims to implement an augmented reality application, the *AR Embryo Atlas*, to aid embryology education and test the hypotheses by studying the effect on usability and motivation in controlled experiments. After summarising related literature in section 1.1, chapter 2 provides background on embryology education and augmented reality. The design and implementation of the *AR Embryo Atlas* application are then discussed in respectively chapter 3 and chapter 4. Chapter 5 then describes the conducted experiment to compare the implemented *AR Embryo Atlas* application with the 3D-PDF files. Results of this experiment are presented and discussed in chapter 6. Finally, chapter 7 provides the conclusion and discusses future research in this field.

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1Interactive models: [https://www.3dembryoatlas.com/](https://www.3dembryoatlas.com/)
1.1 Related work

Various studies have researched the usefulness, advantages and challenges of augmented reality for education, a topic of research that has gained popularity in the past years [7]. Research into augmented reality applications for education is still in an early stage, compared to other education technologies [8]. The studies often focus on development of such an application and only provide basic small-sample studies that lack reliable and valid means of assessment [2].

A recent review on augmented reality in education from Akçayır and Akçayır reports enhanced learning achievement, motivation and enjoyment [7]. Challenges including difficulty of use and technical problems are however also reported, resulting in some conflicting conclusions. Research on motivation, engagement and user experience conducted by researchers from the Waseda University also found that augmented reality enhanced intrinsic motivation and engagement when compared to traditional desktop computer applications [6].

Some research on the use of augmented reality in the specific field of anatomy education has also been conducted. Researchers from the Istanbul and Ataturk Universities found that students that learn using augmented reality had significantly higher achievement and lower cognitive load compared to the control group using traditional methods [9]. This research developed a mobile augmented reality application for neuroanatomy, which all test subjects found to facilitate learning.

A large-scale research conducted at the Catholic University of Valencia reports similar results, students taught using augmented reality had better motivation, attention and test scores [10]. Researchers from the Bond University did not find higher test scores, but did also find increased engagement and immersion [5].
CHAPTER 2

Background

This research aims to implement and research an augmented reality application to aid human embryology education. This chapter provides background on embryology and its current methods of education. Furthermore it provides the definition of augmented reality and background on augmented reality in educational settings.

2.1 Human Embryology education

Human embryology is an important field of study. It is essential in understanding the normal basic human body plan during development, which can explain the relative positions of organs in the adult body and the origin of congenital malformations [1]. These malformations caused up to 20% of all neonatal deaths in the United States in 2013 [11]. Insight into this is thus of considerable clinical interest. Embryology is however difficult to teach, because of the many complex three-dimensional changes that occur over time on both a macro- and microscopic level [12].

A preliminary questionnaire was conducted to psychobiology students at the University of Amsterdam to further research the challenges of embryology education for this research. 87% of the students stated to have experienced difficulties visualizing embryo anatomy. A student remarked, “Only 2D models were available which made clear visualization difficult.” 37% of the students agreed that the embryology course lacked clear visual aids for embryo anatomy and 100% agreed that the use of extensive three-dimensional interactive computer visualisations of embryo anatomy would improve the embryology course.

2.1.1 Current methods of education

Conventional education methods of human embryology include expensive wax models of staged human embryos (see figure 2.1a), embryo and foetus dissections that can provoke ethical objections, clinical studies, images and textbooks [12]. These textbooks are however found to often not be reliable. The textbooks are commonly based on old articles or textbooks, often more than 100 years old, of which the information is mostly impossible to verify [1]. Furthermore, many of this information is originally based on non-human specimens and is wrongfully classified as human.

De Bakker et al. implemented an interactive three-dimensional digital embryo atlas, spanning the first two months of human development [1]. It is designed to replace the increasingly schematic and often incorrect schematics in conventional textbooks on human development [1]. The models in this atlas (see figure 2.1b) are implemented as interactive 3D-PDF files, made to work with the Adobe Acrobat Reader software. This embryo atlas was used in embryology courses at the University of Amsterdam.

This digital embryo atlas is nevertheless not optimal for embryology education. It requires the installation of the large Adobe Acrobat Reader software, which only works on MacOS and
Windows computers, and only allows for somewhat unresponsive and unintuitive interaction with the models. Moreover, Preece et al. conclude that anatomy education using three-dimensional desktop computer-based models is not as effective as more conventional physical models \[13\]. The excellent models created by De Bakker et al. lend themselves for alternative education methods, such as augmented reality.

(a) Wax physical human embryo model.  
(b) 3D digital embryo models \[1\].

Figure 2.1: Examples of current embryology education materials.

### 2.2 Augmented Reality

Augmented Reality (AR) allows virtual objects to be added to the real-life environment. Instead of completely replacing the environment, as is done with Virtual Reality (VR), it supplements it \[14\]. As defined by Azuma, Van Krevelen and Poelman, an AR system has three characteristics \[14, 15\]:

- **AR** provides a combination of real and virtual objects inside a real environment.
- **AR** aligns real and virtual objects with respect to each other.
- **AR** runs interactively, in three dimensions and interactively.

This definition does not limit AR to use particular display technologies, like head-mounted displays or mobile smartphones.

Augmented reality is part of a larger class of technologies often referred to as Mixed Reality (MR). Mixed reality can be described using the Reality-Virtuality continuum by Milgram and Kishino \[16\], see figure 2.2. The opposite ends of this continuum range from a purely real environment to a purely virtual environment (e.g. by means of virtual reality). The surrounding environment is virtual for both virtual reality and augmented virtuality, on the right side of the continuum. Left in the continuum, where augmented reality is found, the surrounding environment is real with only virtual objects added to it.

Figure 2.2: Reality-Virtuality continuum (From Milgram and Kishino \[16\]).
2.2.1 Augmented Reality Learning Experience

The term Augmented Reality Learning Experience (ARLE) is defined by Santos et al. to refer to learning experiences facilitated by AR technologies. ARLEs can be applied to many disciplines in education to simulate experiences that are impractical or impossible when performed physically. These experiences can among other things be too expensive, dangerous or unethical. An ARLE allows real-life like interaction with virtual objects in three dimensions, which can make three-dimensional data more comprehensible and accessible in the classroom. ARLEs can be well applicable to the field of embryology: embryo cadavers are unethical and physical models are expensive and do not allow for much interaction.
Several design possibilities are available for the implementation of the *AR Embryo Atlas* application. These possibilities have been considered before development of the actual application. First, paradigm- and hardware-related considerations are to be made. The application has to be readily accessible and intuitive for learning anatomy. Second, software-related considerations are made to choose the most suitable software components (e.g. engine and frameworks). Finally, content-related considerations have to be made to make the application usable and intuitive, but also feature-rich. These considerations are discussed in more detail in this chapter.

### 3.1 Augmented or Virtual Reality

Literature shows that both augmented- and virtual reality educational tools are promising [5]. Furthermore, Preece et al. suggest that learning the complex three-dimensional spatial relationships of anatomy is more effective using physical models, compared to three-dimensional computer-based models [13]. Physical models are however expensive and impractical for common classroom usage. Augmented reality and virtual reality are potentially a great method of anatomy education. AR and VR closely augment physical models but are not as costly or impractical.

Augmented Reality is found most sufficient for the application of human embryo anatomy for multiple reasons. First, although research conducted by the Bond University in Queensland found no significant differences in learning gains, motivation and engagement between AR and VR in medical anatomy education, a considerable difference between AR and VR was found in the adverse health effects the technologies induced [5]. AR induced only negligible symptoms, whereas the VR application more than often induced symptoms such as general discomfort, dizziness and blurred vision that are commonly referred to as cybersickness [17]. Cybersickness is a prevalent problem with the use of VR, and is evidently not a desirable effect in classroom situations.

Second, augmented reality is more readily accessible in classroom settings than virtual reality. Augmented reality technologies essentially only require a mobile smartphone with a camera at minimum, a piece of equipment owned by (almost) all students nowadays. Mobile augmented reality applications can be easily used both inside and outside the classroom and are accessible to a maximum number of students because no expensive equipment is required, as is with virtual reality applications. A more detailed comparison of current augmented reality hardware is given in section 3.1.2.

Finally, an affordance of mobile AR les with markers, two-dimensional printed images that virtual objects can be virtually projected on (see figure 3.1c), is that it is hypothesised to improve elaboration by integrating both sense of sight and sense of touch into the learning experience [2]. This *vision-haptic visualisation* is further discussed below.
3.1.1 Vision-Haptic Visualisations

Shelton and Hedley theorise that interaction with virtual objects with augmented reality enhances spatial knowledge acquisition [18]. AR systems that use markers allow students to merge the virtual object into the normal viewing perspective. In this way, the advantages of object interaction in real-world environments, e.g. moving the marker or changing its orientation to interact with the virtual object attached to it, are not lost. This interaction with objects is theorised to increase spatial knowledge acquisition by engagement with the additional visuo-motor information [18].

This type of interaction with virtual objects is unique to augmented reality and not present in virtual reality or traditional computer simulations. Virtual reality provides a virtual environment and does thus not allow the effective combination of virtual objects in a real-world environment [2]. In traditional computer simulations, interaction with a virtual model is mediated by means of mouse or keyboard. These operations filter the manipulation of the virtual object and only allow for indirect instead of direct manipulation [2].

3.1.2 Hardware

Augmented reality applications can be developed for several platforms, from mobile smartphones to costly head-mounted displays. As discussed before, accessibility of the application is important and one of the reasons to prefer augmented reality over virtual reality. The required hardware should thus be readily available or affordable. The alternatives to a mobile smartphone are expensive and impractical head-mounted displays like the Microsoft HoloLens 1 (from €3,299) or Metavision Meta 2 2 (from €1,710), displayed in Figures 3.1a and 3.1b. It is not (yet) feasible to use these head-mounted displays with larger groups of students in classroom situations. Moreover, these head-mounted displays do not allow touch input, limiting the interaction with the application. A mobile smartphone augmented reality application (see figure 3.1c) is thus the best option for this application, as most students already have all required hardware.

Figure 3.1: Comparison of current augmented reality hardware.

3.2 Software

Selecting a suitable engine is essential for the development of the augmented reality application and its desired features. Important features of an engine are amongst others the documentation, community, performance, features and build-platforms possibilities.

The Unity and PlayCanvas engines were considered for this research. These engines allow for rapid prototyping and were previously successfully used for developing educational tools at the University of Amsterdam. Unity 3 is a popular cross-platform engine with extensive documentation, stable performance and many features. It requires the Vuforia 4 framework to support developing augmented reality. PlayCanvas 5 is a novel web-based engine that allows for building WebGL web-based augmented reality applications. These applications are available to any device with a modern browser and thus very accessible. Table 3.1 provides a brief comparison between

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1 Microsoft HoloLens: https://www.microsoft.com/en-us/hololens
2 Metavision Meta 2: http://www.metavision.com/
3 Unity engine: https://unity3d.com/
4 Vuforia framework: https://www.vuforia.com/
5 PlayCanvas engine: https://playcanvas.com/
these two engines based on experience from developing preliminary prototypes with both engines, during which the presence of the required features, performance and stability for the augmented reality app was researched and judged as either sufficient or insufficient.

Table 3.1: Comparison of Unity and PlayCanvas engines.

<table>
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<th>PlayCanvas</th>
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<td>Android, iOS, Windows</td>
<td>WebGL (any device)</td>
</tr>
<tr>
<td>Performance &amp; Stability</td>
<td>Sufficient</td>
<td>Insufficient</td>
</tr>
<tr>
<td>Features</td>
<td>Sufficient</td>
<td>Insufficient</td>
</tr>
<tr>
<td>Documentation</td>
<td>Sufficient</td>
<td>Sufficient</td>
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The Unity engine with Vuforia is found most sufficient for this research. It is found most stable and feature-rich. Wu et al. argue that stability and performance of an augmented reality application are of great importance in education [8]. A student is easily deterred by an unstable application, which could naturally cause unwanted lack of engagement and learning. Preliminary prototypes with the PlayCanvas framework resulted in long load-times and overall bad performance of the application. Furthermore, PlayCanvas is in early development and was found to still lack essential features required for the final application. PlayCanvas is however promising for future applications, as it allows for easy deployment and works on any device with a modern browser without any installation.

3.3 Content

The challenge of the content-related considerations is to include more features than the original 3D-PDF files on a smaller screen-space (from desktop computers to mobile smartphones), while enhancing usability. Students should be able to focus on the content and not the use of the application. An intuitive interface with intuitive interactions is thus wanted to achieve this.

The application should include and possibly enhance the original feature of toggling systems and organs in the model. Furthermore, additional features will include:

- Bookmarks of configurations of the systems and organs, to make rapid switching between relevant configurations possible.
- Possibility to move the model by touch, in addition to moving the marker or phone. This allows students to also explore parts of the embryo that are impractical to view from the standard anatomical position.
- General information page with instructions on the use of the application.

Because of the many buttons required for these features, a separate menu screen is designed that allows for intuitive interaction with the models. In this way, all screen-space in the general model view is reserved for the exploration of the model without distracting overlapping menu-buttons. This separate menu is made somewhat transparent to display the model at all times. Direct changes to the model that occur when toggling the systems or organs can in this way immediately be seen. Further buttons to additional screens for bookmarks and information are also added to this menu.

A future addition to the application is supporting models of multiple Carnegie Stages, which is possible because of the extensibility of the application (see section 4.2.1). The temporal changes of the human embryo can be displayed in two ways. One possibility is the use of multiple markers, each corresponding to one supported Carnegie Stage. The fabrication and distribution of these multiple markers lowers the accessibility of the application, but using multiple markers is easy and allows for comparing two models by looking at two markers simultaneously. Another possibility is to use one marker and provide the option to change the model that is virtually projected on it. Although this lowers the required materials and higher accessibility, changes between the stages are harder to directly visualise.
CHAPTER 4

Implementation

The *AR Embryo Atlas* application is created using the Unity game engine. Unity is a cross-platform engine designed to enable the creation of two- or three-dimensional games and environments. It supports programming in both C# and UnityScript, which closely resembles JavaScript. One of the main features of Unity is the ability to export created applications to 27 different platforms: “Build once, deploy anywhere”. Furthermore, Unity works together with Vuforia to enable the development of augmented reality applications.

Applications in Unity conform to a handful of basic concepts, of which the *scene* is the primary concept containing all the environments and menus in the game. A scene in Unity consists of one or more *GameObjects*, the fundamental objects representing anything in the scene. The GameObjects act as containers for their *components*. These components add all the actual behaviours and properties to the otherwise static GameObjects. A specific GameObject with its components can be exported to a general template, a *prefab* in Unity, so it can be dynamically instantiated. To add more sophisticated behaviours to GameObjects, scripts can be used as components.

The C# programming language is used to develop the *AR Embryo Atlas* application. To ensure the modularity of the application’s code, multiple scripts are created containing a multitude of classes. The following sections give a brief overview of the implementation and user experience of the application.

4.1 User Experience

After starting the application, the user initially sees the *model view* with a small (*hamburger*) menu button on the top right-hand corner. In this view, the user can point the camera to the marker to interact with and view the model. Figure 4.1a shows a screenshot of the *model view*.

After expanding the menu using the *hamburger* button, the tree-like structured *toggle menu* for the systems and individual organs is displayed. The menu itself is somewhat transparent, which allows the model to be seen and interacted with while toggling its different systems and organs. The user can in this way clearly see the effect a toggle has on the anatomy model.

In addition to the *toggle menu*, five buttons are displayed on the right-hand side of the *menu view*: the *hamburger* button to toggle the *menu view* itself, a button to toggle rotation by touch, a save bookmark button, a load bookmark button and an information button. Clicking on the latter three of these buttons brings the user to a new menu especially designed for the desired task:

- **Save Bookmark**: menu to export the current configuration of the *toggle menu* as bookmark. A name for this bookmark can be given.

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1Unity Game Engine: [https://unity3d.com/](https://unity3d.com/)
2More information on build-platforms: [https://unity3d.com/unity/features/multiplatform](https://unity3d.com/unity/features/multiplatform)
3Vuforia framework: [https://www.vuforia.com/](https://www.vuforia.com/)

• **Load Bookmark**: menu containing a list of bookmarks saved on the device, with options to load or delete the bookmarks.

• **Information**: page with instructions on the use of the application, as well as information on the authors of the application and the used model.

A screenshot of the menu view can be found in figure 4.1b.

Figure 4.1: Screenshots of both main views in the *AR Embryo Atlas* application.

### 4.2 Interaction with the Model

The **toggle menu** is dynamically generated from the main anatomical model to ensure extensibility of the application. The three-dimensional model is represented as a hierarchical structure of GameObjects in Unity, an example of this structure can be found in figure 4.2. The toggle menu is generated by recursively iterating through this structure, and dynamically instantiating the required buttons for the (sub)systems and organs in a tree-like structure representing the original structure of the model. The instantiated GameObjects, that are required for the toggle menu, are saved as prefabs.

Preliminary prototyping indicated a large difference in performance between transparent and inactive GameObjects in Unity. Setting GameObjects inactive improved framerate, whereas changing transparency only decreased the framerate. It is thus chosen to deactivate corresponding GameObjects when toggling off systems or organs in the model to enhance performance of the application.

#### 4.2.1 Extensibility

It is important to take future growth and future use of software into consideration during development. The *AR Embryo Atlas* application should thus be extensible to allow for the use of different and new anatomy models. A total of 14 different models ranging from Carnegie Stage 7 to 23 were constructed in the original research by De Bakker et al. [1]. The application works with all these models by dynamically generating the menus based on the structure of the current model. Moreover, with the rapid development in computer graphics, more and more three-dimensional anatomical models are constructed. For possible future use of the application in different disciplines, it is important that these models also work with the application.

The *AR Embryo Atlas* application is designed to work with three-dimensional anatomical models of the .fbx file format. For the generation of the menu structure, the model should
consist of a hierarchical structure of systems, sub-systems and organs. This hierarchy can best be represented as a tree-like data structure, in which only the leaves contain actual organs (and the respective meshes) and the nodes are directories representing the system or subsystem. An example of such a hierarchy can be found in figure 4.2, the actual meshes of the individual organs are indicated with *.

- **Carnegie Stage 13**
  - Nervous system
  - Central nervous system
    - Neural canal*
    - Neural tube
      - Mesencephalon*
      - Prosencephalon*
      - Rhombencephalon*
      - Spinal cord*
  - Peripheral nervous system
    - Cranial nerves and ganglia
      - N IX Glossopharyngeal*
      - N V Trigeminal*
      - N VII Facial*
      - N VIII Vestibulocochlear*
      - N X Vagus*
      - N XI Accessory*
      - N XII Hypoglossal*
      - Roots of N VII Facial and N VIII*
    - Spinal ganglia*
  - Respiratory system
    - Respiratory bud*

Figure 4.2: Segment of hierarchy of Carnegie Stage 13 anatomy model.

### 4.3 Bookmarks

The application allows the user to save and load bookmarks of specific configurations of the toggle menu. Such a bookmark should naturally not be lost between runs of the application. To achieve this, the bookmarks are stored in the `persistentDataPath` constant variable: a path to a public directory for data storage that is persistent between runs and updates of the application. A `BinaryFormatter` is used to serialise the object holding the configuration to a binary format for saving purposes. In this way, the data can be easily deserialised and directly used in a later moment.

### 4.4 Documentation

Readable and well-structured documentation is of utmost importance for future development and maintenance of software. The C# code for this research is documented using *Standard C-Sharp XML Documentation*, which incorporates XML tags in the documentation.

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The *AR Embryo Atlas* is designed to aid embryology education at universities. As discussed, previous research suggests that ARLEs can be of use in education. More research on the usability, motivation and student engagement of ARLEs is still required however, as discussed in [7].

This research aims to compare the *AR Embryo Atlas* application with the more traditional 3D-PDF implementation. It is hypothesised that the *AR Embryo Atlas* enhances the motivation of students in comparison to the 3D-PDF files, as suggested in similar studies in this field [5, 6]. It is furthermore hypothesised that the usability of the *AR Embryo Atlas* is higher than that of the 3D-PDF files. This can however be influenced by the participants’ prior knowledge of embryology and experience with augmented reality [5].

### 5.1 Method

The participants, 20 first-year Psychobiology students (16 female, 4 male; age $M = 21, SD = 7.63$) from the University of Amsterdam without detailed prior knowledge of embryology, were randomly assigned to two conditions. In one condition the *AR Embryo Atlas* application was used and in the other the 3D-PDF files were used. The participants were individually provided instructions on the application to use, after which several (simple) tasks using the application were given by the researcher. The participants were asked to use the application for 9 minutes and to continue exploring the application and its features after finishing the provided tasks. After completing these tasks, a final questionnaire was conducted to the participants. Throughout the entire experiment, the participants were free to ask the researcher for assistance. The researcher also kept track of relevant observations throughout the experiment. The applications ran on devices (a Huawei Android Smartphone for the *AR Embryo Atlas* or a MacBook Pro for the 3D-PDF files) that were administered by the researcher. All participants thus used the same device, eliminating possible external influences to usability caused by different devices.

Because of the straight-forward nature of the applications, with the primary functionality of navigating through the embryo anatomy, common measurements of usability (e.g. error count or time spent on tasks) do not provide an accurate measurement of the usability of the application, but more so measure embryology knowledge. Furthermore, additional features implemented in the *AR Embryo Atlas* application are not present in the original 3D-PDF files and can not be used for comparison in this research. A psychometrically validated questionnaire was thus found most applicable for the comparison between the use of the *AR Embryo Atlas* and the 3D-PDF files, and was used in this research.

The online questionnaire constructed for this research most importantly assesses intrinsic motivation and usability of the application. In addition, several demographic (e.g. age and current studies) and general questions were conducted. These general questions surveyed both prior experience with ARLEs and embryology, as well as the attitude towards use of augmented reality.

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1A paper version of the Google Forms questionnaire can be found in Appendix A.
reality in education, as performed by Sumadio and Rambli [19]. The same questionnaire was conducted to both conditions.

5.1.1 Motivation Measurement

The Intrinsic Motivation Inventory (IMI) was used to assess the motivation of the participant during the use of the application. The IMI is a multidimensional tool that measures the participant’s intrinsic motivation and experiences of activities during laboratory experiments [20]. The use of the IMI in this field was suggested by Santos et al. and successfully applied to measure and compare motivation towards different educational applications by Iwata et al. [2, 6].

The IMI offers several subscales, of which five were found relevant for this research: interest/enjoyment, perceived competence, effort/importance, pressure/tension and value/usefulness. Only the interest/enjoyment subscale is considered to directly measure the self-reported intrinsic motivation. The perceived competence and effort/importance are positive predictors and the pressure/tension is a negative predictor of intrinsic motivation. Finally, the value/usefulness subscale was used to measure the usefulness of the application to the participant. This is useful because students are more likely to become self-regulating and internalize in learning-activities they find more useful to themselves [20].

This resulted in a questionnaire of 30 questions, all belonging to one of the above subscales. A seven-point Likert scale, ranging from not true at all to very true, was used to answer the questions. The questions were slightly modified from the original IMI questionnaire to be applicable to both the computer application as well as the mobile augmented reality application. For example, the original question “I enjoyed doing this activity very much.” was altered to “I enjoyed using the application very much.”.

5.1.2 Usability Measurement

Usability is often defined as a combination of the components effectiveness (outcomes), efficiency (interaction process) and satisfaction (users’ attitudes and experiences) [21, 22]. Many conventional tools to measure these components of usability (e.g. QUIS) are not well applicable to the usability of augmented reality experiences. A relevant psychometrically validated questionnaire that is applicable to both more traditional computer software (the 3D-PDF files) and mobile augmented reality applications is required for this research.

A psychometrically validated usability questionnaire created by Dorribo-Camba and Contero was found appropriate for this specific research [23]. This questionnaire separately measures a combination of the components effectiveness and efficiency, and satisfaction in line with the definition above. It was successfully used to compare a mixed reality application with a desktop application in a later study by Cumba et al. [24].

The questions in the questionnaire were again slightly modified to be applicable to both the computer application as well as the mobile augmented reality application in this research. For example, the original question “The Augmented Reality application is stable and works well (doesn’t freeze).” was altered to “The application is stable and works well (doesn’t freeze).”. An additional question was added to further research the differences in completeness between the applications, this question was taken and modified from the CSUQ questionnaire: “The application has all the functions and capabilities I expect it to have.” [25]. A five-point Likert scale, ranging from strongly disagree to strongly agree, was used to answer the questions.
None of the participants had attended a course on embryology prior to the research. Several stated that some basic embryology knowledge was attained in other courses however. Furthermore, the participants stated to only have little experience with augmented reality technology: 35% of participants has used augmented reality occasionally, 45% has rarely to very rarely used augmented reality and 20% indicated to have never used augmented reality before. In line with previous findings by Sumadio and Rambli [19], the general attitude towards augmented reality learning experiences is positive, the majority of participants (90%) totally agrees that augmented reality is useful for education and 10% partly agrees. These results include the participants of both conditions and were asked after the experiment. The Carnegie Stage 13 model was used in the applications during the experiments.

### 6.1 Motivation

Figure 6.1 shows the mean scores and standard deviations of the measured subscales of the Intrinsic Motivation Inventory. The modified IMI questionnaire was conducted to the participants after completing tasks using either the 3D-PDF files or the AR Embryo Atlas. A seven-point Likert scale, ranging from 1, not true at all, to 7, very true, is used. As stated in the Intrinsic Motivation Inventory, the results of some questions are reversed [20].

![Image of bar chart showing mean scores and standard deviations for Interest, Enjoyment, Perceived Competence, Effort, Importance, Pressure, Tension, and Value Usefulness for AR Embryo Atlas and 3D-PDF files.]

Figure 6.1: Intrinsic Motivation Inventory subscale scores

The AR Embryo Atlas scored better than or equal to the 3D-PDF files on all the subscales of the IMI. A significantly large difference between the 3D-PDF files and the augmented reality...
application (AR: $M = 6.06, SD = 0.42$; 3D-PDF: $M = 5.26, SD = 0.70$) is found for the interest/enjoyment subscale, the only subscale directly measuring the intrinsic motivation. Also value/usefulness shows a significant difference (AR: $M = 6.63, SD = 0.32$; 3D-PDF: $M = 5.79, SD = 0.22$), indicating that the participants regarded the AR Embryo Atlas as more useful and valuable.

The perceived competence (AR: $M = 5.3, SD = 0.72$; 3D-PDF: $M = 5.18, SD = 1.01$) and effort/importance (AR: $M = 4.28, SD = 0.66$; 3D-PDF: $M = 4.28, SD = 0.68$) subscales, that are theorised to positively predict intrinsic motivation, show little to no difference. The augmented reality application scored lower on the pressure/tension subscale (AR: $M = 1.86, SD = 0.24$; 3D-PDF: $M = 1.94, SD = 0.30$), that is theorised to negatively predict intrinsic motivation.

### 6.2 Usability

Figure 6.2 summarises the results of the usability questionnaire in the components discussed in section 5.1.2. The usability questionnaire was conducted alongside the IMI, after completing tasks using either the 3D-PDF files or the AR Embryo Atlas. A five-point Likert scale, ranging from 1, strongly disagree, to 5, strongly agree, is used.

![Figure 6.2: Usability component scores](image)

The augmented reality application scores better than the 3D-PDF files on all usability components. Only a slight difference was found for effectiveness and efficiency between the two applications (AR: $M = 4.45, SD = 0.10$; 3D-PDF: $M = 4.40, SD = 0.18$). The participants were however significantly more satisfied with the AR Embryo Atlas ($M = 4.8, SD = 0.12$), than with the 3D-PDF files ($M = 4.3, SD = 0.24$). Furthermore, the participants scored the AR Embryo Atlas as significantly more complete (AR: $M = 3.90, SD = 0.99$; 3D-PDF: $M = 3.20, SD = 1.03$).

The general opinion of both applications is unanimously positive. On a scale from 1, very bad, to 5, excellent, the participants rated the 3D-PDF files an average of 4.4 ($SD = 0.52$) and the AR Embryo Atlas an average 4.7 ($SD = 0.48$). No one rated lower than 4, good.

### 6.3 Further comments from participants

The participants were asked for further comments on the used application and general opinion on augmented reality use in education after finishing the questionnaire. The participants were especially positive about the AR Embryo Atlas, remarking that the application was fun and intuitive to use. Both applications provided great insight into the anatomy of the embryo. Several participants explicitly mentioned the desire for such applications during their studies.
One participant remarked “Having a different way of getting information is always nice, and if it is fun to do it helps even more. I actually really enjoyed this program and liking something you learn always helps.”.

Other participants commented that “I think it [an augmented reality learning experience] helps a lot to be able to visualise the systems and be able to ‘play’ around with them instead of just seeing it in 2D on a piece of paper.”, “They [augmented reality learning experiences] provide insight into the structure of organs compared to each other (sic) in a 3D plane.” and “I think an application like this one helps visualising the embryo anatomy a lot better than books do, as this application uses 3D. That works better for me.”.

Finally, a participant explained that “In my opinion, AR tools can improve learning, but should not work as a replacement. For some students like me, who have bad visual memory, reading information can help understand the content better than seeing it.”.

6.4 Discussion

6.4.1 Motivation

The results of the Intrinsic Motivation Inventory are in line with the hypothesis, the augmented reality application enhances the motivation of students in comparison to the interactive computer models. The augmented reality application scored significantly higher on the interest/enjoyment subscale. This subscale is the direct self-report measurement of intrinsic motivation [20]. This result indicates that the augmented reality application enhanced intrinsic motivation, which benefits academic performance [26].

Little to no difference was found between the augmented reality application and the 3D-PDF files on the perceived competence and effort/importance subscales, that are theorised to positively predict motivation. The perceived competence subscale is assessed using questions like “I was pretty skilled at using the application.”. As augmented reality is a novel technology to most participants, it is possible that more time is required to get used to the application and to reap the benefits of its theorised intuitiveness and ease of use. Participants displayed little interaction with the marker and often still resorted to customary touch-based interaction with the model. The effort/importance subscale assesses the effort put into the activity and its importance. The lack of difference in this subscale can be explained by the laboratory setting and low difficulty of the assigned tasks.

The pressure/tension subscale is theorised to be a negative predictor of intrinsic motivation. Although this score is significantly lower than that found in a previous study assessing ARLEs using the IMT by Iwata et al. [6], thus meaning that the augmented reality application induced less pressure and tension in the participants, little difference between both applications was also found for this subscale. Again, possibly caused by the inexperience with the novel augmented reality technology.

The final subscale, value/usefulness, measures the experienced usefulness and value of the application to the participant. This was also assessed in regard to the field of embryology using questions like “I think that using this application is useful for gaining better understanding of human embryo anatomy.”. The augmented reality application also scored significantly better on this subscale, meaning that the participants experienced it as more useful and valuable to them. This is beneficial because students are more likely to become self-regulating and internalize in learning-activities they find more useful and valuable to themselves [20].

6.4.2 Usability

Little difference in usability was found between the AR Embryo Atlas and the 3D-PDF files. The participants scored the AR Embryo Atlas only slightly better on effectiveness and efficiency. A possible explanation for this is that the participants were inexperienced with the relatively new mobile augmented reality technology used in the AR Embryo Atlas application. The participants
indeed stated to only have little experience with augmented reality technology: 35% of participants has used augmented reality occasionally, 45% has rarely to very rarely used augmented reality and 20% indicated to have never used augmented reality before. Traditional technology as used in the 3D-PDF files is more generally used and thus more familiar to the participants.

As hypothesised, the participants reported more satisfaction with the augmented reality application than with the 3D-PDF files: augmented reality was found more valuable to improve embryology, more engaging and interesting to the participants and provided more advantage over traditional education materials.

The augmented reality application was also rated as significantly more complete (i.e. the application has all expected functionalities). This was as expected; as the augmented reality application build upon the features of the original 3D-PDF files and additional features (e.g. toggling of individual organs and bookmarks) were implemented.
Augmented reality learning experiences can be used in embryology education to overcome limitations and obstacles that are present in current teaching methods. Conventional embryology teaching methods are limited due to financial and ethical constraints, and a recent desktop computer application, that implements excellent recently published anatomy models, does not utilise the affordances offered by augmented reality. The rapid development of augmented reality technology allows for accessible and intuitive mobile augmented reality applications. Such an application, displaying the recently published embryo anatomy models, is implemented and compared to the desktop computer application for this research.

The augmented reality application provided a significant increase in intrinsic motivation and was found more useful and valuable to the participants in comparison to the interactive desktop computer models. No significant increase in efficiency or effectiveness was found, possibly caused by the participants’ little experience with the novel augmented reality technology. The participants were however significantly more satisfied with the augmented reality application and rated it as more complete.

The findings of this study show benefits of augmented reality learning experiences over more traditional desktop computer simulations and great potential for future use in (embryology) education. The augmented reality application was indeed found to significantly enhance motivation in the participants, but did not yet fully result in higher usability over the desktop computer application. More research is required to further research whether the found increase in motivation, perceived value and satisfaction translates to increased learning gains as well.

7.1 Future Research

Research on augmented reality learning experiences is still in its early stages, compared to the more mature technologies used in education [8]. More research on augmented reality aided learning and its uses in embryo anatomy education is thus needed. This research should include a larger sample size and be conducted over a longer period, so participants can get more acquainted with the augmented reality application. Furthermore, future research could, in addition to intrinsic motivation and usability, directly measure learning benefits of augmented reality over traditional methods. It is critical to carefully construct the learning method for the control group to best resemble the ARLE, eliminating the possible influence of other variables on the outcomes.

Assessing learning benefits of educational technology is often done using a conventional pre-test and post-test experiment design. Such an experiment design effectively measures what or how much new knowledge is learned but often fails to describe how it was learned. Jenkinson suggests the additional use of more fine-grained evaluative tools, such as eye tracking or brain imaging, to make more sense of this black box that is interacting and learning using educational technologies [27].

The results and feedback acquired in this research can be used to further improve the application. The participants rated the efficiency and effectiveness of the AR Embryo Atlas high
and were also satisfied with the application. The absolute completeness of the application does however still require improvements, additional features that were out of the scope of this research can be added. Participants suggested adding a quiz system, cross- and longitudinal-sections and clickable organs for more information. Furthermore, another possible feature suggested by a domain expert is the ability to synchronise bookmarks between students and teacher, to share answers or useful configurations and allow for more collaboration in the classroom.
Bibliography


APPENDIX A

Questionnaire

Post-experiment Evaluation Questionnaire
Questionnaire on experiences and usability of the educational application for embryology. Please fill in as accurately as possible, based on the experience with the application. Take your time, feel free to ask any question during the questionnaire. Form is handled strictly anonymously.

Thank you very much for your time and cooperation.

*Required

General Information
General information of the participant, to be filled in and asked out by the researcher prior to the experiment.

1. Condition: *
   Mark only one oval.
   - 3D-PDF
   - AR

2. What is your age? *

3. What is your gender? *
   Mark only one oval.
   - Female
   - Male
   - Other

4. What do you currently study or have you studied? *

5. I have attended a relevant course on embryology. *
   Mark only one oval.
   - Yes, and completed it.
   - Yes, but have to retake.
   - No.
6. Subjective Experience with Application

Several statements about your experience with the application are displayed below, please indicate how true each statement is for you, using the following scale: 1: not true at all, 4: neither true nor untrue, 7: very true.

Mark only one oval per row.

<table>
<thead>
<tr>
<th>Not true at all</th>
<th>Not true</th>
<th>Somewhat not true</th>
<th>Neither true nor untrue</th>
<th>Somewhat true</th>
<th>True</th>
<th>Very True</th>
</tr>
</thead>
<tbody>
<tr>
<td>Using the application was fun.</td>
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<td>I thought using the application was quite enjoyable.</td>
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<td>I believe working with this application could be beneficial to me.</td>
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<td>I think working with this application is important.</td>
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<td>I felt pressured while working with the application.</td>
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<td>I was pretty skilled at using the application.</td>
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<td>I think this application important to use because it can improve my knowledge of embryo anatomy.</td>
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<td>I think that using this application is useful for gaining better understanding of human embryo anatomy.</td>
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<td>I think I am pretty good at using this application.</td>
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<td>It was important to me to do well using the application.</td>
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<td>I put a lot of effort into this.</td>
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<td>I felt very tense while using the application.</td>
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<td>I believe this application could be of some value to me.</td>
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<td>I was anxious while working with the application.</td>
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<td>While I was using the application, I was thinking about how much I enjoyed it.</td>
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<td>I did not feel nervous at all while using the application.</td>
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<td>I didn't try very hard to do well at using the application.</td>
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<td>Using the application did not hold my attention at all.</td>
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<td></td>
<td>Not true at all</td>
<td>Not true</td>
<td>Somewhat not true</td>
<td>Neither true nor untrue</td>
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<td>I am satisfied with my performance of using the application.</td>
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<td>I enjoyed using the application very much.</td>
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<td>I tried very hard on using the application.</td>
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<td>I would describe using the application as very interesting.</td>
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<td>I think using this application could help me to better understand human embryo anatomy.</td>
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<td>I felt very relaxed in using the application.</td>
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<td>I thought using this application was boring.</td>
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<td>I didn't put much energy into using the application.</td>
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<td>After working with the application for awhile, I felt pretty competent.</td>
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<td>I would be willing to use this application again because it has some value to me.</td>
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<td>This was an application that I couldn't use very well.</td>
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<td>I think I did pretty well at using this application, compared to other students.</td>
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7. Usability of Application *
Several more statements about your experience with the application are displayed below, please indicate how true each statement is for you, using the following scale: 1: strongly disagree, 2: disagree, 3: neither agree nor disagree, 4: agree, 5: strongly agree.
Mark only one oval per row.

<table>
<thead>
<tr>
<th>Strongly disagree</th>
<th>Disagree</th>
<th>Neither agree nor disagree</th>
<th>Agree</th>
<th>Strongly agree</th>
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<tbody>
<tr>
<td>The use of this application is interesting and engaging.</td>
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<td>The application is responsive (no lag in the screen when manipulating virtual models).</td>
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<td>The manipulation of the virtual model is easy and intuitive.</td>
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<td>This application is suited to help students comprehend embryo anatomy and improve visualisation skills.</td>
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<td>The application has all the functions and capabilities I expect it to have.</td>
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<td>The use of this application in an Embryology course is valuable and useful to improve the understanding on embroylogy topics.</td>
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<td>The use of this application provides a significant advantage over traditional written materials.</td>
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<td>The visual quality of the 3D models is adequate. The models are clear and easy to recognize.</td>
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<td>The application is stable and works well (doesn't freeze).</td>
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<td>The use of an application such as this can increase attention and motivate students to study Embryology.</td>
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8. Overall opinion of the application: *
Mark only one oval.
- Very bad
- Bad
- Average
- Good
- Excellent
9. I think Augmented Reality (AR) tools are useful in education. *  
   Mark only one oval.  
   ☐ Not Sure  
   ☐ Disagree  
   ☐ Partially Agree  
   ☐ Totally Agree  

10. Please elaborate on the above: *  

11. How much have you used Augmented Reality technologies before? *  
   Mark only one oval.  
   ☐ Never  
   ☐ Very Rarely  
   ☐ Rarely  
   ☐ Occasionally  
   ☐ Frequently  
   ☐ Very Frequently  

12. Do you have a smartphone? If yes, which one?