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ORIGINAL RESEARCH

Educational Potential of Augmented Reality Mobile Applications for Learning the Anatomy of the Human Body

Santa Dreimane[1] · **Linda Daniela**[1]

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Abstract
The use of different technologies and technological solutions for learning purposes is no longer a novelty in the educational environment. Digital teaching materials are being developed that can be used both in classroom activities and for providing students with opportunities for independent learning. However, alongside these materials, there are various additional opportunities that can be used in the educational process to make learning more interesting and to motivate learners to become more actively involved in the construction of their knowledge. One is mobile applications, where augmented reality (AR) solutions enable the anatomy to be learned interactively by accessing knowledge traditionally provided through two-dimensional teaching aids, or sometimes through static three-dimensional objects. Mobile applications with AR solutions allow to understand the anatomy from both the external and internal dimensions of the body without being in a specific laboratory or anatomy laboratory (anatomicum). This article summarizes the evaluation results of 41 applications analyzed in the first evaluation phase, and seven mobile applications that met all of the advanced selection criteria were selected for in-depth analyses using a developed evaluation framework with 19 criteria from three areas: (a) technological performance, (b) information architecture, and (c) educational value.

Keywords Mobile application · Augmented reality · Learning anatomy · Educational value · Evaluation rubric

1 Introduction

Augmented reality (AR) is an enhanced version of reality created by the use of technology to overlay digital information on an image of something being viewed through a device, such as a smartphone camera (Merriam-Webster, n.d.), and it can be used on a wide array of media in the form of desktops, smartphones, and mobile devices in different areas, including to promote learning (Forsyth 2011). Researchers believe that AR solutions have

✉ Linda Daniela
linda.daniela@lu.lv

Santa Dreimane
santa.dreimane@lu.lv

[1] University of Latvia, Riga, Latvia

great potential for educational use (Cowling and Birt 2018) because it is possible for them to provide high-quality visualizations that can help improve learning processes (Morrison et al. 2011), which points to the importance of graphical solutions in the development of AR products. AR solutions provide interactive experiences by adding virtual elements to the real world (Höllerer and Feiner 2004), which enhance students' ability to be active participants in the learning process and participate in knowledge building as AR solutions can support the self-control, self-study abilities and autonomy in learning activities of students (Karagozlu 2018).

AR solutions for education are currently being analyzed in different contexts. Innovative solutions are being sought to increase students' knowledge of particular concepts and to make the learning process more interactive and to analyze specific areas of knowledge where AR solutions can help to achieve learning goals, which can be voluntarily set by the students themselves or sourced from the curriculum. The use of such applications has been analyzed in physics (Cai et al. 2017), biology (Hwang et al. 2016), chemistry (Cai et al. 2014), and mathematics (Bujak et al. 2013). An article has also been written on using AR applications for learning anatomy (Rodriguez-Pardo et al. 2015). Most of these articles analyze small groups of students and the conclusions made are very optimistic about the possibilities of AR solutions.

There are some authors who assume that most AR technologies are designed with no actual educational agenda in mind (Yuen et al. 2011), and a literature analysis on the use of AR solutions in education shows that it is necessary to deepen research specifically in the field of education to clarify curricula, assessments, teachers' professional and digital competence (Biezā 2020), and teacher training to work on these solutions (Koutromanos et al. 2015). This indicates that despite the numerous articles describing the benefits of using AR in the organization of the learning process, it is also necessary to understand the educational value of a given application and their shortcomings to back them up with teachers' seamless presence. The potential of AR solutions also needs to be evaluated so that they can be used as tools for scaffolding learning and for the development of metacognition (Sweller 2006), rather than just to entertain and fascinate people.

The field of AR research can be viewed in three main categories—technical solutions, information architecture and applications of AR. This study analyses AR applications from educational perspective and specifically AR applications for learning purposes, because it comes very challenging for educators to find and navigate the AR learning applications in order to ensure that the set learning objectives will be achieved. This article focuses on AR solutions for learning anatomy available through mobile devices, where connection to the content on the application is possible anytime, anywhere and without the need to use any other physical objects for anatomy learning to take place. A developed and approbated evaluation rubric (Daniela and Aierken 2020; Daniela 2020), refined for the purposes of this study, is used to analyze the various augmented applications for learning the anatomy of the human body from three different aspects that are synergistically complementary: (a) technological performance, (b) information architecture, and (c) educational value but all these dimensions are evaluated from the learning perspective to merge together new methods of knowledge searching and the principles of knowledge acquisition (Bal 2018) and to ensure that technological perspective is not taken in forefront but a wide variety of technology enhanced methods of knowledge searching are supporting learning.

The article is based on the idea that AR solutions can be incorporated successfully in the learning process, but before they can be used, their capabilities and limitations need to be identified. The following *research objective* can thus be posited—to evaluate mobile applications for learning anatomy in AR mode to understand their potential from educational

perspective and the limitations that should be borne in mind. The related *research question* can therefore be expressed as follows: what is the utilization and educational potential of mobile applications for learning anatomy in AR mode?

This paper is structured as follows: the analyses of the latest literature on mobile application usage possibilities for learning purposes; further the explanation of the research design and methods used is given which is followed by the research results and a discussion of the results and the final part is devoted to the conclusions drawn from the data collected during the research.

1.1 Research Approach

1 To achieve the goal of the study, the authors used an evaluation rubric, which was updated to add more structure (see ''Appendix 2'').
2 Applications were searched for on the App Store using the keywords "AR anatomy" and "augmented reality anatomy". At the time of the study, 41 applications were found to be available, and after their evaluation, seven were further evaluated according to the evaluation rubric.
3 The results were analyzed from a possible learning perspective using quantitative and qualitative data analysis methods.

2 Augmented Reality Apps for Educational Purposes

AR solutions can be used successfully in education as they stimulate interest in the learning process (Bressler and Bodzin 2013; DeLucia et al. 2012; Collins 2009). They also have the potential to change the timing and the environment of the learning, offer innovative learning methods, and are believed to have an impact on learning processes (Billinghurst and Dunser 2012). AR solutions allow students to access visual information that they would not see if only physical objects were used in the learning process (Nischelwitzer et al. 2007), and if they are not available, the learning process has to be based only on theoretical explanations of the subject which can play a role in problematic knowledge acquisition (Zghida et al. 2019).

In a literature review on the use of AR in education, Chen et al. (2017) concluded that research has demonstrated the positive impact of AR on learning motivation, which provides an improvement in learning outcomes, and related that AR solutions are rich in graphics and other notable interaction features. Altinpulluk (2019) analyzing articles on the impact of AR on education, also found that it has a huge impact on learning processes, because AR solutions help students to learn anytime and anywhere, and can support students with visualization problems to understand huge systems and micro-organisms that would otherwise be difficult to imagine. Controversially, Garzón and Acevedo (2019) found in a literature review on the use of AR solutions in education that there is only one article in which AR is evaluated from the perspective of improved learning outcomes; all the others are analyzed in a specific context, analyze specific cases, or analyze literature on possible outcomes. They also concluded that most of the articles analyzed did not mention the use of quantitative research methods, indicating that the optimistic results obtained could not be generalized. Those conclusions do not mean that there is no potential in use of different AR solutions but they should be perceived with a caution that different technological

methods can help to differentiate the way of knowledge is accessed but knowledge acquisitions should be supported.

This study on the use of mobile applications with AR solutions for learning anatomy has a multifold nature because it is necessary to explore how interactive learning tools (in the context of this study, mobile AR applications) can be used to motivate student learning and support knowledge development; to understand what AR applications' limitations are and to replace them with other pedagogical activities, thus creating a blended learning approach; to demonstrate how institutional barriers to learning, such as time-bound and curricular learning, can be overcome, and to promote the exploratory learning nature of learners; and to provide AR mobile application developers with guidelines to help build applications with greater educational value. This research article deals with the first two above-mentioned aspects, and the latter two will be analyzed in later stages of this research project.

3 Research Design and Methodology

This study was conducted from a phenomenological perspective, using the approach developed by Hitzler et al. (2004) who emphasize the subjective experience of the researcher in the field which essentially is utilised (explicitly and reflexively) as a tool for collection and interpretation of data, more precisely, it used the principles of transcendental design to analyze applications for learning anatomy (Moustakas 1994), and a hermeneutic design (Wernet 2014) was used for the interpretation of the data obtained from the analysis.

In the first stage of the selection of augmented reality mobile apps, the digital distribution platform "App Store" was searched using the keywords "AR anatomy" and "augmented reality anatomy". Searches were made for augmented reality apps for both phones and tablets in order to view the wider market. Information on the apps offered by the App Store was inserted in an Excel file and sorted by the title of the app, the device on which it can be used (phone and/or tablet), the existence of an additional in-app charge or purchase, language, and whether an augmented reality mode is provided in the app.

In the second stage of selecting apps for further analysis, apps that were provided in English, offered an augmented reality experience mode and did not have in-app purchases or did not include a fee that prevented the app from being analyzed were selected. Also, it was essential that the app could be used by anyone, anywhere with a phone or tablet, that it could be used remotely, and that it did not require any specific objects or QR code to access the content. The selected apps were not tested on specific learners or to assess specific knowledge acquisition, but were analyzed from the perspective of their educational potential.

The procedure to evaluate the applications was as follows—both researchers evaluated all the selected apps according to the criteria chosen by using their subjective personal experience as educators based on an approach developed by Honer (2004) and Hitzler and Eberle (2004). After the first phase of evaluations the researchers discussed the evaluation results to come to consensus and data was summarized in a table, which was later analyzed hermeneutically.

Criteria for the evaluation of augmented reality applications for learning anatomy were developed and divided into three groups (see Fig. 1):

1 Technological performance (8 criteria);

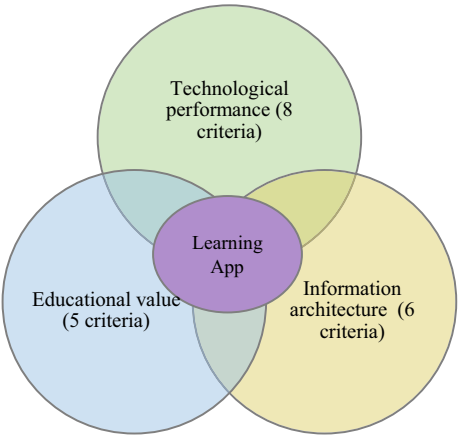


Fig. 1 Groups of criteria for the evaluation of the learning apps

2 Information architecture (6 criteria);
3 Educational value (5 criteria).

There was also a criterion indicating the age group for which the learning app may be more suitable, but as there were only seven apps suitable for in-depth evaluation, information on the age groups was collected but was not specifically analyzed. All the criteria were evaluated by choosing one of three levels. These levels were indicated by numbers from 1 to 3, where 1 indicated the lowest level of the criterion, 2 indicated the medium level, and 3 indicated the highest level. Only in the last row of criteria, where an opinion on the age group of the app was given, could more than one answer be chosen. Each criterion has different descriptions for the levels (see ''Appendix 2"), which are selected according to the evaluator's opinion based on the extensive literature analysis and in the evaluation, the authors' personal educational experiences were used as an evaluation frame. This structure of the evaluation framework was borrowed from Stevens and Levi (2013) and customized to the specifics of the apps. As shown in Fig. 1, all criteria and their groups interact with each other, influencing the information perception process.

The obtained quantitative data on the training applications were analyzed by calculating the mean for each application, for each criterion, as well as for each group of criteria separately.

4 Research Results and Discussion

In order to evaluate and conceptualize the existing and potential usability of the augmented reality apps for learning anatomy, 41 apps were detected in the first stage of app selection (see ''Appendix 1'') that corresponded to the chosen keywords "AR anatomy" and "augmented reality anatomy". Of these apps, 25 contained in-app purchases, for example, a particular book ($n=4$), a T-shirt ($n=2$), a Merge Cube ($n=1$), a torso of a plastic body ($n=1$), worksheets ($n=1$), a specific box ($n=1$), and others. One app provided an individual system that required the payment of a fee to view or use it, and a free trial for a few days was offered by another app. One app was designed for a specific exhibition that a user had to be at and another asked for a special code, but it did not explain how to get it. All the

apps which were not fully available for evaluation were excluded from in-depth analyses. Of the selected 41 applications, 21 were designed just for phones and 10 just for tablets. 10 applications could be used on both phones and tablets.

In the second stage of the selection of the anatomy apps, seven applications met the selection criteria (see Table 1) and were fully analyzed, using the criteria for the evaluation of AR applications for learning about the structure of the human body shown in "Appendix 2". Table 1 provides a description of each application and information on the body systems and layers that can be explored within the applications.

Initially, the average scores of all criteria were calculated without distinguishing specific groups of criteria. After that, the mean for each mobile app was calculated and then for the separate criteria groups within each app. Thereafter, the averages for each set of criteria and for each criterion were calculated separately, taking into account the results of all applications selected for the in-depth analysis.

The mean values of all the apps are shown in Fig. 2. The highest score was shown by "The Brain AR" and "Humanoid AR" (2.21), while the lowest score was displayed by "Sigvaris Group Vein" and "Figure Anatomy" (1.68). It should be mentioned that these two applications with the lowest average score are not intended for the direct study of the anatomy of the human body in compulsory education; "Figure Anatomy" is designed to represent the human body for those who study drawing in order for them to better understand the body in motion, while "Sigvaris Group Vein" is an app developed by the company Sigvaris to educate people on leg vein health by offering treatment options, medication instructions, and promoting their own medical compression garments but these apps were included in evaluation as the structure of them have some educational potential.

The mean values of all apps in the three criteria groups are shown in Fig. 3. An average score was calculated for each group, which is provided by the average score of the criteria for each application within the relevant group. Within the group of technological performance aspects (8 criteria), the mean score of all learning apps was 2.38, which is the highest score of all three criteria groups. The least attention was paid to the information architecture aspects (6 criteria) that gave an average score of 1.62 for all learning apps analyzed. As the results of the data calculation show, similarly little attention was paid to the educational value aspects when designing anatomy applications. The evaluation results of the five educational value criteria resulted in a mean value of 1.69, which reveals that during the design and development of a learning application, less attention is paid to education, which could ensure the product's efficient and effective use and the acquisition and persistence of the knowledge that the app could provide and it confirms the conclusions made by Garzon and Acevedo, 2019, that such solutions can't replace human pedagogical work, at least in this stage of development.

For the technological performance criteria, "Luke AR" and "The Brain AR" both had the same highest score (2.63), followed by "Human Anatomy 4D" with a mean value of 2.50. The lowest score for the technical criteria was recorded by the "Sigvaris Group Vein" application (2.13). Three apps had the same score of 2.25: "Figure Anatomy", "Virtual Skeleton" and "Humanoid AR+".

For the information architecture criteria group, the mean score for all learning apps was 1.71. "Humanoid AR+" had the highest mean score (2.50), followed by "The Brain AR" and "Human Anatomy 4D" (2.00). "Figure Anatomy" had the lowest possible mean value (1.00), followed by "Luke AR" (1.17), pulling down the overall score of this group.

Within the educational value criteria group, the highest mean value (1.80) is shared by four apps: "Human Anatomy 4D", "The Brain AR", "Luke AR" and "Humanoid AR+". The lowest mean score of 1.40, which is still very close to the highest score in

Table 1 List of mobile apps for learning anatomy in AR mode selected for in-depth analysis

	Name	Description
1	Human Anatomy 4D	In augmented, virtual and mixed reality modes, it offers to learn about the human body and body systems, showing muscle, skeletal, digestive, urinary, circulatory, and nervous systems and lymphatic nodes
2	The Brain AR	Offers to explore the layers of the head from the skin, muscles and skull down to the inner areas of the brain
3	Figure Anatomy	Offers to assist with drawing human characters for both beginner and expert artists by showing the human body in different positions
4	Luke AR	Offers to explore the internal organs and five major body systems
5	Virtual Skeleton	Offers to explore the 25 major bones of the human body
6	Sigvaris Group Vein	Provide a leg vein anatomy tool and information about venous disease with brochures, video clips and links to Sigvaris medical compression garments and Sigvaris compression bulletins
7	Humanoid AR +	Offers to explore and examine the human body system in detail – namely, the skeletal, digestive, nervous, and other systems

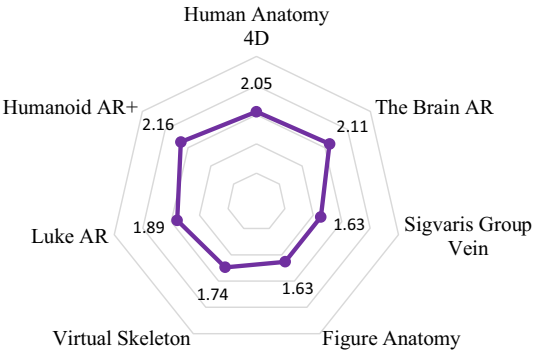


Fig. 2 Mean values of all learning apps for all criteria groups

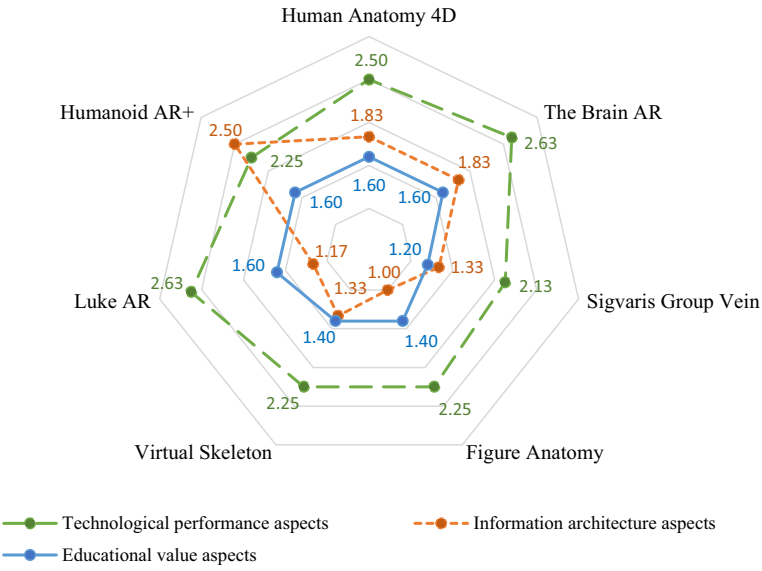


Fig. 3 Mean values of all learning apps by group of criteria

the same group, was recorded by the "Sigvaris Group Vein" app and results of evaluation show that the lowest score for all apps are given in educational criteria. The technological and information architecture aspects can catch students' attention, can support learning motivation, can rise the interest on subject and support knowledge development but if there is no logical sequence of information flow, if there is no features which challenge to find out more information and no option for knowledge test then there can be supported development of factual knowledge without reaching metacognitive level of knowledge. In such a learning space teachers have to become skillful orchestrants to manage, in real time, multi-layered activities in a multi-constraints context (Dillenbourg 2013).

All the evaluation criteria were further analyzed to determine which had the highest mean scores and which had the lowest in the selected applications (see Fig. 4). In the technological performance criteria group, the highest mean score (3.00) was recorded by the criteria "Use of the app", "The graphics of the app", and "Perception of the app", and the

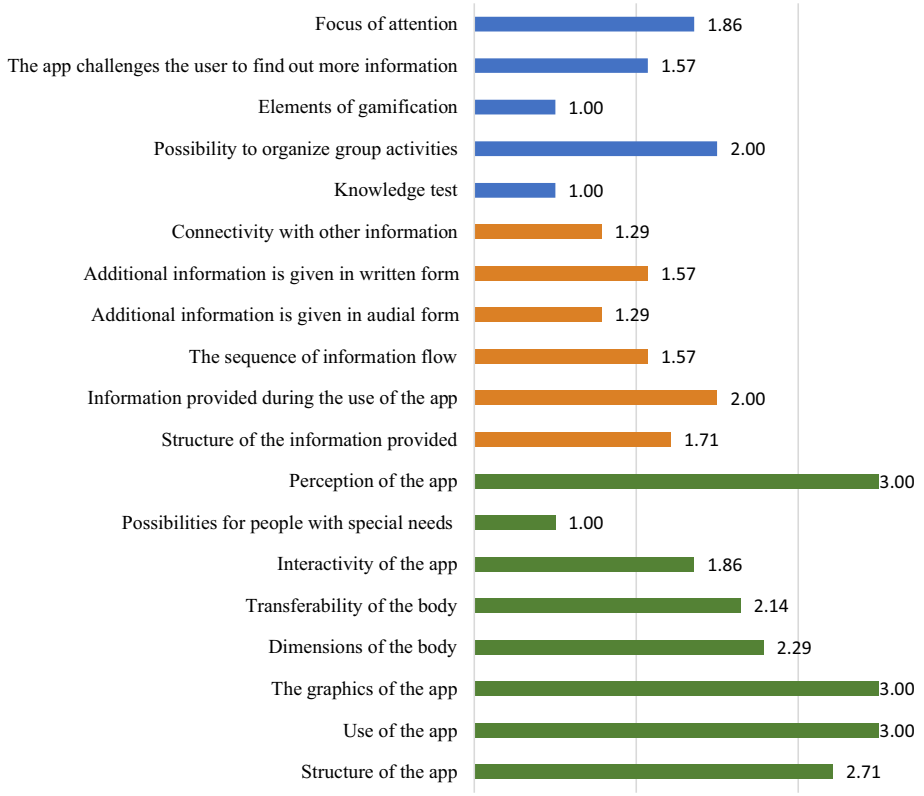


Fig. 4 Mean values of all criteria (blue: technological performance criteria; orange: information architecture criteria; green: educational value criteria)

lowest score was for the criterion "Possibilities for people with special needs" (1.00) followed by "Interactivity of the app" (1.86).

In the group of information architecture aspects, the highest result was for the criterion "Information provided during the use of the app" (2.00), followed by "Structure of the information provided", "Additional information is given in written form" and "The sequence of the information" (1.57). The criteria "Additional information is given in audial form" and "Connectivity with other information" had the lowest mean score (1.29) which confirms the idea that metacognitive thinking should be supported by other means of pedagogical work to scaffold the development of metacognitive knowledge.

In the educational value criteria group, the highest mean score was for the criterion "Possibility to organize group activities" (2.00) and the next highest criterion was "Focus of attention" (1.86), while the lowest possible mean score (1.00) was recorded for "Elements of gamification" and "Knowledge test". The results show that the important part of educational process—possibility to get the feedback is missing and it can cause the problems for students who have lover level of motivation, who have problems with merging different parts of information and it leads to conclusion that AR apps can support learning of well motivated students but other students' motivation should be supported by activities orchestrated by teachers.

5 Hermeneutic Data Analysis

A hermeneutic analysis (Wernet 2014) of the comments recorded during the evaluation of the applications was carried out next. The seven mobile apps that met the selection criteria were analyzed (see Tables 2, 3, 4, 5, 6, 7, 8) and included in the in-depth evaluation with descriptions of the technological performance, information architecture and educational value aspects of each application based on individual evaluation made by both researchers and consensus reached after the discussions. The mean values of each app and of each criteria group are also given. Next to the application title is the mean score given for all the criteria and in the column of criteria group is indicated the mean of the particular group of criteria. Tables are arranged in a sequence of evaluation not according to mean value.

It has to be taken into account that these applications have been made available for Apple phones, and mobile devices with other operating systems may offer a different range of augmented reality mobile applications. Applications from other operating systems were not evaluated in this research because of technical limitations as only Apple phones and iPad were available but we believe that evaluation criteria can be applied for different applications as well.

Some of the evaluated apps allow the user to move with their mobile device and walk around the augmented human body while it stays still in one place ("Human Anatomy 4D", "Virtual Skeleton", "Luke AR", "Humanoid AR+"). Some of the apps offered static representations of the human body, which can be moved around by using a finger on the screen, but the user cannot walk around the body ("The Brain AR", "Figure Anatomy") and explore its different sides and layers. "Sigvaris Group Vein" can be fully and qualitatively used in AR mode on an iPad, but this may limit the number of users of the app. A phone may be a better and more accessible way to provide everyone with an augmented reality experience in the learning process.

The information provided in the apps about the subject is easy to understand if any information is given at all. "The Brain AR" only offers names and descriptions for the brain, not for other body parts. Apps like "Human Anatomy 4D", "Virtual Skeleton" and "Humanoid AR+" provide only the names of body systems and organs. "Sigvaris Group Vein" provides the names of the veins of the human leg in Latin and makes suggestions to the user to watch videos or read materials about venous disorders and compression products. In "Humanoid AR+", information about the digestive system and the names of bones and parts of the digestive system is provided. If you want to see the names of parts of the body's other systems, you have to register and pay. The apps that offer nothing but visual information are "Luke AR" and "Figure Anatomy".

All analyzed apps require more information with educational value, which would be an addition to their well structured and graphically well designed visual material. This leads to the conclusion that most of these apps were built while mainly focusing on the graphics, visualization and technological aspects, without incorporating information architecture or educational value in the apps. As the apps lack additional information or at least basic information that can teach something to a user, they do not provide any kind of knowledge test. None of the apps were created to challenge the user to find out more information, and also none of them provide any kind of gamification elements to engage or motivate the user or stimulate their persistent attention.

The aims of the apps have to be noted as well, because not all of the analyzed apps are used for teaching anatomy. The "Sigvaris Group Vein" application is designed for

Table 2 Evaluation of *"Human Anatomy 4D"*

App	Criteria group	Evaluation
Human Anatomy 4D Mean = 2.05 	Technological performance aspects Mean = 2.50	The app is available for iPhone and iPad in augmented reality and also virtual and mixed reality modes, for which special glasses are needed. The use of the app is free of charge and in-app purchases are not required for the augmented reality mode The content is well structured and it is easy to understand how to use the app, although there is no tutorial on how to use it, except for the first step about creating a person's body. The graphical elements are well structured and the visualizations are of good quality It is possible to walk around the body, to transverse the body in a few details and to move the body parts around and see them from different dimensions, so it is easy to perceive the material The app offers to reset the body if you cannot put body parts or systems back in the right place by yourself. However, it resets everything you have done at once. You cannot go back step by step You can move the menu to another place in the room, but you cannot do the same with the body you have created; you have to shut down the app and start over to place the body in another place The material has been prepared for the general public, and there is no possibility to switch the way in which the information is provided so that it could be used by people with special needs
	Information architecture aspects Mean = 1.83	The information provided is well structured and easy to understand, but there is not much information given about the human body parts or organs. Some parts of the information can be skipped or changed; for instance, you can select or refine the given body systems to observe them separately and closer Some additional information is given in written form, but there is no option for an audial form If you want to see the name of the organ or body system, you have to hold a finger down on it while reading, then it disappears, but sometimes the description is out of sight; this is not practical
	Educational value aspects Mean = 1.60	This app allows you to organize group activities, but the small nature of the device limits the number of participants, so it is only suitable for small groups There are some elements that challenge the user to find out more information about the topic, but these are not used on a regular basis. Also, there are some parts where the focus of the user's attention is stimulated, but this does not occur throughout the experience Negative aspects of the educational perspective are the lack of a knowledge test and elements of gamification not being used to engage and motivate the app's user

Table 3 Evaluation of "*The Brain AR*"

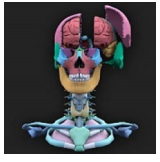
App	Criteria group	Evaluation
The Brain AR Mean = 2.16 	Technological performance aspects Mean = 2.63	Available for iPhone in AR and VR mode. The app is free and does not contain in-app purchases The content is well structured and it is easy to understand how to use the app. The graphical elements are well structured and the visualizations are of good quality, but they are not very realistic. To distinguish the skull bones and parts of the brain, they are displayed in different colours The torso of the human is static and moves together with the screen so that it is in front of you whatever you do. It is easy to rotate the head and see it from different dimensions (outside and inside) and to transverse the head in smaller details There is no possibility to switch the way in which the information is provided so that people with special needs could use the app. The only possibility to switch the way the information is provided is to get audial information about the brain, which could help those users who perceive audial information better or who have vision problems
	Information architecture aspects Mean = 1.83	All the information given is provided in an easy to understand way The sequence of the information flow can be partly changed according to the decision of the person who explores the material. Additional information is given in audial form, but this is just about the brain, not other layers or systems of the body, and you cannot stop the sound until it finishes the description. But it is possible to change the visual material if you wish to explore it more. Unfortunately, no additional information is given in written form about parts of the body other than the brain
	Educational value aspects Mean = 1.60	It is possible to organize group activities for small groups if you consider that a phone screen allows up to three people to participate There are some parts where the focus of the user's attention is stimulated, but this does not occur throughout the experience because of the lack of information about the visual material There are some elements that challenge the user to find out more information, but these are not used on a regular basis This app does not offer the possibility to test the knowledge gained and does not use elements of gamification to engage the user

Table 4 Evaluation of "*Sigvaris Group Vein*"

App	Criteria group	Evaluation
Sigvaris Group Vein Mean = 1.63 	Technological performance aspects Mean = 2.13	Available for iPhone and iPad in AR and 3D mode. The app is free and does not contain in-app purchases, but recommends buying products if necessary The content is well structured, it is easy to understand how to use the app, and the visualization of the app is of good quality It is possible to view the leg in a bit more detail and to see the veins of the leg all together or separately from a few outside dimensions Interaction with the app is not provided, but overall it is easy to perceive the app's material The material has been prepared for the general public, and there is no possibility to switch the way in which the information is provided for people with special needs
	Information architecture aspects Mean = 1.33	No information is provided about the muscles or bones that the user can see, there is only visual material. Only the Latin names of the veins are provided for those users who can understand them Some additional information is given in audial form and in videos. Some additional information is also given in written form about the Sigvaris Group's products, but not about anatomy-related subjects The sequence of the information flow cannot be changed according to the decision of the person who explores the material
	Educational value aspects Mean = 1.20	This app also allows you to organize small group activities for up to three people. But there is no possibility to test the knowledge included, nor are there elements of gamification The material does not challenge the user to find out more information. The material is interesting, but there are no specific features to capture the attention of the user

Table 5 Evaluation of "*Figure Anatomy*"

App	Criteria group	Evaluation
Figure Anatomy Mean = 1.63 	Technological performance aspects Mean = 2.25	The app is available for iPhone and iPad in augmented reality mode. The app is free and does not contains in-app purchases The content is well structured and it is easy to understand how to use it. The graphical elements are well structured as well, and the visualizations are of good quality It is possible to move the body and see it from different outside dimensions in different positions, as well as to change the light and shadows, which is useful for sketching, but it is not possible to transverse the body in detail, which is important for learning anatomy The material has not been prepared for use by people with special needs
	Information architecture aspects Mean = 1.00	There is a good technological structure, but unfortunately no structured information is provided, just visual material The sequence of the information flow can be changed according to the decision of the person who explores the material No additional information in audial or written form is given
	Educational value aspects Mean = 1.40	There is no possibility to test the knowledge included in the app, but its purpose is to assist, not to give knowledge about the human body and its parts from an anatomical perspective It is possible to organize group activities for small groups of up to three people, but if it is connected to a bigger screen, people can draw in larger groups as well Elements of gamification are not used in the app, and the material does not challenge the user to find out more information

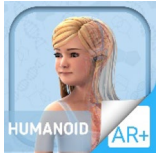
Table 6 Evaluation of "*Virtual Skeleton*"

App	Criteria group	Evaluation
Virtual Skeleton Mean = 1.74 	Technological performance aspects Mean = 2.25	The app is available for iPhone and iPad in augmented reality mode. The app is free and does not contain in-app purchases, but there are constant pop-ups and advertisements The content is structured, but although the structure is not very logical, you can understand how to use the app The graphical elements are well structured and the visualizations are of high quality It is easy to move the skeleton and see it from different angles, but the app does not allow you to transverse the body in detail The material has been prepared for the general public, and there is no possibility to switch the way in which the information is provided
	Information architecture aspects Mean = 1.33	No structured information is provided, just the name of each bone of the human body without any additional explanation or information The sequence of the information flow can be changed according to the decision of the person who explores the material by pointing a red dot at the bone that you are interested in No additional information in audial or written form is given
	Educational value aspects Mean = 1.40	It is possible to organize group activities for small groups of up to three people There is neither a knowledge test included nor gamification elements, so it does not challenge the user to find out additional information The focus of the user's attention is stimulated by pointing a red dot at a bone, but you have to be very precise

Table 7 Evaluation of "*Luke AR*"

App	Criteria group	Evaluation
Luke AR Mean = 1.84 	Technological performance aspects Mean = 2.63	The app is available for iPhone and iPad in augmented reality mode. The app is free and does not offer in-app purchases The graphical elements as well as the content are well structured and easy to understand. The visualizations of the human body are of high quality It is easy to move the body around and see it from different sides and different dimensions (outside and inside), and it is easy to transverse the body in smaller detail It is easy to perceive the material, but it has not been prepared for people with special needs
	Information architecture aspects Mean = 1.17	No information is provided in the app about the human body, body parts and body systems; there is just visual material. No additional information is given in audial or written form either. Because of this, the information architecture aspects cannot be evaluated
	Educational value aspects Mean = 1.60	It is possible to organize group activities of exploring the human body for small groups of up to three people The lack of information could challenge the user to find out some additional information, but it could also reduce their interest in the app The app does not provide the possibility to test the knowledge gained and also does not include any gamification elements

Table 8 Evaluation of "*Humanoid AR +*"

App	Criteria group	Evaluation
Humanoid AR + Mean = 2.16 	Technological performance aspects Mean = 2.25	The app is available for iPhone and iPad and offers in-app purchases to view additional body systems It is easy to understand how to use the app, the graphical elements are well structured and the visualizations are of high quality, so it is easy to perceive the material It is possible to transverse and see the body and its parts in smaller detail from a few dimensions. The digestive system and skeleton are available for free, but you have to pay to see other body systems and their descriptions. The app offers the option to switch the gender of the human The material has been prepared for the general public, and there is no possibility to switch the way in which the information is provided
	Information architecture aspects Mean = 2.50	The information provided in the app is well structured and easy to understand This is one of the rare apps that provides an option to go back a step, and some parts of the information flow can be skipped or changed The app provides information about the body system you are observing and also the names of the bones or parts of the digestive system. If you want to see the names of parts of other body systems, you have to register and pay No additional information is given in audial form
	Educational value aspects Mean = 1.60	There are some parts where the focus of the user's attention is stimulated, but this does not occur throughout the experience, and there is also no possibility to test the knowledge included There are some elements that challenge the user to find out more information, but these are not used on a regular basis. No elements of gamification can be found in the app either It is possible to use the app with small groups of up to three people

commercial purposes, while "Figure Anatomy" is not designed to learn anatomy, but instead allows the user to draw the human body without the presence of a human model.

It should also be highlighted that none of the analyzed apps were designed for people with special needs, and this could be another goal to strive for when developing a learning application.

All the results collected and analysed during this stage of the research show that most effort on app development is placed on technological aspects but less effort to support learning and the results of the analysis of AR apps echo those of Quinn (2019), that the role of the teacher is still very important because the virtual and augmented solutions available today cannot completely replace human pedagogical work, as concluded also by Garzon and Acevedo (2019).

6 Conclusions

Augmented reality solutions have the potential to increase students' motivation, it can be used to catch students' attention and raise their interest, and the possibility for them to actively participate in the development of cognition; thus, being active participants in the learning process, they can promote discovery-based learning.

However, there are problems discovered. For instance, teachers who may want to apply the content used in the application to meet specific learning needs or to meet the needs of specific students cannot change the structure of the material themselves, despite the fact that some researchers already pointed out such a problem in 2009 (Bergig et al. 2009).

Similarly, AR solutions can be a challenge for children at a young age who have developed concrete thinking and who rely on their perceptions to make decisions, and it can be confusing for them to see various symbolic meanings (Flavell and Miller 1993). It is also important to keep in mind that it is necessary to follow step by step instructions while learning; for example, when acquiring procedural knowledge, it is necessary that the instructions are included in the learning material itself so that the learner understands the sequence of their actions. Unfortunately, most of the apps analyzed in this study did not offer such a sequential structure. In some cases, they were based on the intuitive logic of the user, and while instructions for the app's technical use were available upon opening some of them, none of them included learning instructions, indicating the need for the seamless presence of a teacher who orchestrates the learning process.

Although AR solutions have great potential to stimulate interest and motivation and encourage the use of various forms of active learning, such as discovery-based learning, the results of the analysis indicate that the currently available AR applications do not yet provide a way of providing learners with independent learning, which highlights the need to develop solutions to enable students to construct their own knowledge and conceptual models that are consistent with the content of the learning they are acquiring. This is in line with the conclusions of Di Serio et al. (2013).

6.1 Research Limitations

The study has limitations, the first of which involves selecting AR applications by selecting only those applications that are available to the user free of charge. The second limitation is that despite the fact that the evaluation of AR was carried out using structured evaluation principles, it involves an aspect of subjectivity, since the evaluation was carried out by researchers with a certain experience in technology and educational experience as the valuation is largely due to the evaluator's current knowledge. This limitation can be mitigated by the continuation of research activities, the expansion of the research base and the development of deeper details of the evaluation section, but this limitation cannot be completely eliminated.

These findings provide a basis for further research, where AR apps can be used in educational settings to assess their impact on learning outcomes, students' metacognitive load, learning preferences, learning outcomes and so on.

6.2 Further Steps

This current research about mobile apps, wherein anatomy can be learned through augmented reality solutions, is being conducted to identify the learning potential and the potential limitations of using these apps. In the next steps, further research is needed to analyze which compulsory education curriculum topics can be mastered through these solutions, as well as whether these applications have any impact on knowledge acquisition and how it is necessary to organize pedagogical work so that the use of apps has advanced learning outcomes.

Appendix 1

See Table 9.

Table 9 List of augmented reality applications for learning anatomy found on the App Store

1	Human anatomy 4D
2	Human anatomy interactive
3	Discover human body AR
4	Learn skeleton 3D anatomy
5	Complete anatomy platform 2020
6	AR anatomy 4D +
7	Easy anatomy: 3D canine anatomy
8	Touch surgery: surgical video
9	Anatomy and sports massage
10	The brain AR
11	Figure anatomy
12	Anatomy and Tai Chi AR
13	BSI 2 DAR anatomy
14	Anatomy AR
15	Virtual-Tee by curiscope
16	Anatomy and yoga AR
17	AR Anatomy by Jump Simulation
18	Anatomy AR book
19	Anatomy and stretching
20	Anatomy ARVR
21	Human anatomy for iPhone
22	Humanoid 4D +
23	Mr. Body for MERGE Cube
24	Popar human anatomy
25	Know our anatomy by OOBEDU
26	Skin and bones
27	Victor the torso
28	Sitee
29	Pearson's off the page
30	Luke AR
31	Virtual skeleton
32	Complete heart
33	BSI 3D AR Anatomy
34	Human anatomy explorer
35	Human anatomy explorer AR
36	Deepscope ultrasound simulation
37	Sigvaris group vein
38	Allergan AR
39	Humanoid AR +
40	Respiratory system
41	Respiratory system AR

Appendix 2

See Table 10.

Table 10 Criteria for the evaluation of augmented reality apps for learning anatomy

	APP		
Technological performance criteria			
App can be used on	iPhone	iPad	iPhone and iPad
	1	2	3
Comment:			
An in-app purchase	Yes	No	–
	1	2	–
Comment:			
Structure of the app	The content is well structured	The content is structured but the structure is not logical	The content is fragmented and not structured according to some kind of logic
	3	2	1
Comment:			
Use of the app	It is easy to understand how to use the material	It is not very understandable how to use the material	It is hard to understand how the material should be used
	3	2	1
Comment:			
The graphics of the App	The graphical elements are well structured and visualizations are of high quality	The graphical elements are randomly structured and visualizations could be of a better quality	The graphical elements are poorly structured and visualizations are of low quality
	3	2	1
Comment:			
Dimensions of the body	It is easy to move the body and body parts and see them from different dimensions (outside and inside)	It is possible to move the body and body parts and see them from different outside dimensions	It is possible to see the body and body parts only from a few outside dimensions
	3	2	1
Comment:			
Transferability of the body	It is easy to transverse the body in smaller details	It is possible to transverse the body in a few details	It is not possible to transverse the body in detail
	3	2	1

Table 10 (continued)

	APP		
Comment:			
Interactivity of the app	There are different forms of interactivity	There is some interactivity	People cannot interact with the material
	3	2	1
Comment:			
Possibilities for people with special needs	The material has been prepared in a way that people with diverse special needs can use it, and it is clearly indicated how to use it	The material has been prepared in a way that people with some specific special needs can use it, but it is not available for all groups of people with special needs, and it is indicated which groups can use it	The material has been prepared for the general public, and there is no possibility to switch the way in which the information is provided
	3	2	1
Comment:			
Information architecture criteria			
Perception of the app	It is easy to perceive the material	The material is well prepared but sometimes it is hard to perceive due to the complexity of the information	It is hard to perceive the material
	3	2	1
Comment:			
Structure of the information provided	The information provided is well structured and easy to understand	Some parts of the information are well structured but some information lacks structure and it is not easy to understand	There is no structured information provided
	3	2	1
Comment:			
Information provided during the use of the app	All the information is given in an easy to understand way, even without previous knowledge of the topic	Some parts of the information are given in an easy to understand way, but some parts are hard to understand without previous knowledge of the topic	The information is hard to understand (due to complexity, fragmentation or other problems)
	3	2	1

Table 10 (continued)

	APP		
Comment:			
The sequence of information flow	The sequence of the information flow can be changed according to the decision of the person who explores the material	Some parts of the information can be skipped or changed	The sequence of the information flow cannot be changed according to the decision of the person who explores the material
	3	2	1
Comment:			
Additional information is given in audial form	A lot of additional information is given in audial form	Some additional information is given in audial form	No additional information is given in audial form
	3	2	1
Comment:			
Additional information is given in written form	A lot of additional information is given in written form	Some additional information is given in written form	No additional information is given in written form
	3	2	1
Comment:			
Connectivity with other information	There is smooth connectivity with other parts of the information, other body parts, organs, etc	There is fragmented connectivity with other parts of the information, body parts, organs, etc	There is no connectivity with other information
	3	2	1
Comment:			
Educational value criteria			
Knowledge test	The possibility to test knowledge is included in different parts of the material and on different aspects of the information provided	There is a possibility to test knowledge, but it is only on a few aspects of the material	There is no possibility to test the knowledge included
	3	2	1

Table 10 (continued)

	APP		
Comment:			
Possibility to organize group activities	It is possible to organize group activities for an unlimited number of participants	It is possible to organize group activities for small groups (up to three people)	It is not possible to organize any group activities while interacting with the AR experience
	3	2	1
Comment:			
Elements of gamification	Elements of gamification are used to attract people and to keep them focused	Some elements of gamification are used but on a fragmented basis	Elements of gamification are not used
	3	2	1
Comment:			
The material challenges the user to find out more information	The material is developed in a way to challenge the user to find out more information	There are some elements that challenge the user but these are not used on a regular basis	The material does not challenge the user to find out more information
	3	2	1
Comment:			
Focus of attention	The material is developed in a way that keeps the user's attention focused on the experience all the time	There are some parts where the focus of the user's attention is stimulated but not throughout the experience	The material is interesting but there are no specific features to capture the attention of the user
	3	2	1
Comment:			
The age group by which the app could be used	Adults (18+)	School-age children (7–18)	Minors (up to 7)
	3	2	1
Comment:			

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