Augmented reality-based learning for the comprehension of cardiac physiology in undergraduate biomedical students

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by acting as an idealization of reality, based on theoretical abstractions, and simplified comparisons of a specific phenomenon (10).

There is evidence that visual perception and visualization supports mental integration processes (30). Indeed, both perception and imagination use spatial arrangements when visualizing objects (5). Ergo, the ability to move to a comprehensive understanding depends on three processes: 1) scanning (changing the focus of attention on the object or image); 2) zoom in or zoom out (to appear closer or farther from the element); and 3) rotation (360° rotation along any axis) allowing a correct perception of the objects. Visual representations do more than display concepts in a model: they help focus attention on salient features. They also support cumulative reasoning by helping create a visual image that can be animated in the mind (22). Yu et al. pointed out the consequences of inadequate meta-visual capabilities in elementary school students (41). This argument relies on the fact that, in general, students have problems in using models to represent an integrated process, such as cardiac contraction, which involves knowledge of anatomy, physiology, and biochemistry that must be integrated at different levels of representation (6, 36). Additionally, levels of representations (macroscopic, microscopic) become second nature to the teacher, which requires additional demands on learners already challenged by the abstract nature of concepts (34).

One documented strategy for learning complex structures in human anatomy involves the construction of anatomical models (16, 17, 25). Muscular clay modeling (7, 21), transverse sections of clay organs (26), three-dimensional virtual models (3, 38, 39), and the positive influences of augmented reality (AR) on the performance of tasks in anatomy classes have also been documented (14, 15). However, underlying cognitive mechanisms of reasoning and strategies employed by students when solving changes in scales from molecular, micro-, and macroscopic visualization problems are less documented (23, 40).

Although there is evidence supporting the influence of AR in clinical education (14), the cognitive mechanisms and strategies that students use to solve problems related to changes in macroscopic, microscopic, and molecular levels are less understood (23, 24). The potential benefits of AR to teach cardiac physiology are reflected in the available resources to teach anatomical sciences. In this sense, resources of real-scale
three-dimensional (3D) models of anatomical sections have been implemented with good learning results in undergraduate students (16, 25). Thus AR represents an instructional avenue that replaces, in part, the lack of cadaveric material. On the other hand, several studies indicate that AR have additional applications (20), such as the visualization of structures in three dimensions (5, 14). In recent years, the tendency is to combine technologies with AR to achieve the creation of AR applications that enhance portability. Portability gives students immediate access to the information, for example, in mobile devices (27), which gives the opportunity to provide a visual guide for completing multiple tasks (41). However, the combination of AR and a mobile application being used in educational settings remains an open area of research.

The questions guiding this study are as follows: 1) What effects do AR learning modules have on students in the understanding of cardiac function?; and 2) Does the promotion of visualization via AR learning modules optimize the learning experiences of students in the short term? The objective of this research was to evaluate if an AR-based learning sequence improves the student’s ability to learn from 3D, zoomable, and rotational cardiac images.

**MATERIALS AND METHODS**

**Participants.** The sample consisted of 101 students from the Pontificia Universidad Católica de Valparaíso, Chile, who were enrolled in their third year of undergraduate biomedical sciences course work. A total of 58 students (31 women, 27 men) were assigned to the experimental group, and 43 (25 women, and 18 men) to the control group. Both groups ranged from 20 to 22 yr of age. All participants agreed to participate in the study by signing an informed consent form. Additionally, the Ethics Committee of the Pontificia Universidad Católica de Valparaíso approved the study.

**Physiology course context.** Cardiac contraction is a topic during the third year for biomedical students as part of the Human Physiology module. The module surveys all aspects of functional systems and clinical gross physiology. As part of its pedagogical structure, the module includes a 4-h-long weekly laboratory practice session. The same graduate teaching assistant and undergraduate student were available for the control and experimental groups. Both the control and experimental activities were performed during the 4-h weekly laboratory session. The control group performed a basic teacher-centered reinforcement activity about the heart contraction process using PowerPoint slides. To test if both groups (experimental and control) had the same learning abilities, the students answered a preexperimental quiz consisting of 15 true or false questions 1 wk before the implementation of the AR experience. All questions were related to basic circulatory system and hemodynamic concepts (Table 1).

**Development of the application and learning activities.** The experimental group performed four activities using the SPECTO resource (from Latin, meaning look or watch) developed by the authors. These activities allowed students to explore anatomical views of a high-definition human heart including a “zoom-in” feature for closer inspection of the microstructures and internal anatomy by touching the screen to manipulate perspective. Students also visualized physiological aspects of heart contraction using a 3D model of the heart that included external and internal structures and buttons to increase or reduce the speed of heart contractions. Finally, in the last activity, the app allowed student to manipulate molecular aspects of cardiac contraction by visualizing the whole process inside the cardiac cell. Scenarios and learning objectives given to both the control and experimental groups are described in Table 2, and an example of the first activity is illustrated in Table 3. Software Unity 3D 5.1.37 (37) was used because it offers free features, versatility in various platforms, including layout, light effects, and sound programming. Vuforia SDK version 5.0.6 (29) was used for the incorporation of AR. Both software programs are free for noncommercial purposes. Both are available at: https://play.google.com/store/apps/details?id=cl.PUCV.SpectoCardiaco. The SPECTO application included a teacher’s guide and a printed student guide (also available in PDF format for distribution), and an Android application package (APK) to be downloaded onto any smartphone or tablet device with an Android 4.1 operating system or higher. Once the application was downloaded onto the device, it could be activated by the student. The SPECTO allowed students to visualize content by means of AR, videos, two-dimensional animations, and/or simulations.

**Data collection.** A basic questionnaire related to the entire process of heart contraction in humans was given to students as a pretest and posttest to both the control and experimental groups. This questionnaire included the following questions: 1) Can you draw the cardiac contraction process?; and 2) How can you explain the whole cardiac process and its function in the human body? Drawings of the pretest and posttest were analyzed with Kozma and Russell’s (13, 33) levels of representation to evaluate learning progressions. Figure 1 shows examples of the student’s drawings. From the theoretical levels defined by Kozma and Russell, we established that level 1 drawings corresponded with a simple description. For example, by asking students to represent the phenomenon of cardiac contraction, a level 1 drawing would contain physical characteristics and isomorphic and iconic descriptions of the phenomenon at a single time point. Level 2 drawings contain only symbols. For example, students explain the process of cardiac contraction with parts of the heart, including at least one variable (e.g., flow), and interaction with external aspects (e.g., physical requirements). However, level 2 is still at the macroscopic level. Level 3 representation is defined by a syntactic use of formal representations in the drawings. That is, the student explains the process of cardiac contraction by drawing parts of the heart, including

| Question | True | False |
|----------|------|-------|
| 1. Cardiac output is the amount of blood pumped out by each ventricle. | | |
| 2. Heart rate may change by sympathetic influence. | | |
| 3. Blood from body tissues goes to the pulmonary passing through the heart. | | |
| 4. The chambers that discharge blood of the heart are the ventricles. | | |
| 5. Blood returns from the body through the superior and inferior vena cavae. | | |
| 6. The aorta is the largest artery of the body. | | |
| 7. Heart rate is regulated only by parasympathetic inputs. | | |
| 8. Heart contraction initiates by a hyperpolarization. | | |
| 9. The greatest longitudinal area in the circulatory system is in capillaries. | | |
| 10. The lumen of an artery is larger than in a comparable vein. | | |
| 11. The flow through true capillaries is controlled by precapillary sphincters. | | |
| 12. The most important method of capillary exchange is simple diffusion. | | |
| 13. The baroreceptors and chemoreceptors are located in the carotid and aortic sinuses. | | |
| 14. The systemic circulation is controlled by vasodilatory and vasoconstrictor factors. | | |
| 15. Changes in heart rate might be influenced by postural changes. | | |

All questions were related to basic circulatory system and hemodynamic concepts.
variables mentioned in the previous level. However, the student is able to change the scale (from macro- to microlevel), explaining the interactions with other cellular structures and processes, even if the structure and processes are not interpreted correctly. Level 4 representation shows the student’s explanation of the process of cardiac contraction, parts of the heart, flow variables, interaction with external aspects, and physical requirement, among others. The student is able to include molecules, such as CO₂, O₂, or Na⁺ and Ca²⁺ ions and their relationship with the contraction process. Therefore, the student explains the phenomenon, solves the problem, and makes predictions. Level 5 representations implicate the solution of a problem by choosing a previous representation to explain the phenomenon to a third party. Level 5 representation also includes graphs, equations, or schemes to express complementary or equivalent ideas. In addition, the student identifies clinical factors (e.g., infarction, heart failure, others) that affect contraction processes, concepts of cardiac output and the effect of mechanical stress on ventricular wall remodeling, and wall mechanical properties on cardiac function in normal and dysfunctional hearts.

Once students completed the entire learning sequence, both of their visual representations (i.e., the ones created during the pre- and postphases) were analyzed by a panel of experts who were blinded to the treatment groups. To determine the level of affinity between the evaluations of the expert panel, Cohen’s kappa index was employed (1, 35). The index is easy to interpret and uses values between 0 (i.e., total disagreement) and 1 (i.e., maximum agreement). However, it has the disadvantage that, even if two observers were to classify independently, a certain degree of agreement could occur by chance. The strength of the agreement in classifying drawings was 0.61 (pretest) and 0.80 (posttest) for the experimental group, and 0.90 (pretest) and 0.88 (posttest) for the control group.

Activity evaluation. The student evaluation guideline was an opinion questionnaire with four Likert-type statements: strongly disagree (SD), disagree (D), agree (A), and totally agree (TA). Students in the experimental group were asked to evaluate their experience with the activities that involved questions related to the function, anatomy, and the process of cardiac contraction. Students were also asked to describe strengths, weaknesses, and suggestions for future implementations. The opinion questionnaire was applied online at the end of the semester.

Data analyses. Data were analyzed using STATA software (Stata, version 12.0; StataCorp). Descriptive statistics of mean, standard deviations, frequencies, and percentages were calculated. Additionally, normality of the data distribution was also evaluated using the Shapiro–Wilk test. To compare the control and experimental group, a t-test was used. Moreover, a t-test was also used to compare groups by gender. Test for symmetry was used for paired nominal data (student’s responses) in a contingency table. Significant results were reported when a significant change from answer A to answer B was found. In this study, symmetry test was used to evaluate the variations in the representation levels between pretest and posttest for the control group and the experimental group. The significance level was set at P < 0.05.

RESULTS

Control and experimental groups did not show statistical differences in the preexperimental test. Using an initial preexperimental quiz 1 wk before the experiment, the two groups were evaluated according to the basic knowledge of anatomy of the circulatory system and hemodynamic concepts and basic biochemistry. Results indicate that there were no significant
differences in the preexamination score between the control and experimental group when students answered the preexperimental 15-question true-false quiz (Table 1). This suggests that both groups, at the onset of the study, possessed a similar set of skills and knowledge base. Additionally, a t test was performed to compare male and female participants. Results likewise indicate no statistical difference in the mean score and distribution (Fig. 2). All scores were measured using a base grade point average that ranged from 1 (very deficient) to 7 (outstanding), according to the academic grading system in Chile where 1.0–1.9 is very deficient, 2.0–2.9 is deficient, 3.0–3.9 is less than sufficient, 4.0–4.9 is sufficient, 5.0–5.9 is good, and 6.0–7.0 is outstanding.

Augmented reality-based learning improves the comprehension of cardiac physiology concepts. A symmetry test demonstrated no differences in the distribution of pre- and posttest distribution in the control group; however, experimental group distribution was statistically significant \( P < 0.0001 \). Figure 3 shows substantial differences in the frequency distribution of students’ drawing (levels 1 to level 5) for pre- and posttests. Levels 1–3 showed a similar trend for the pretest of the control and experimental groups, although the percentage of students situated in level 1 was higher in the control group for the pretest. The percentage of students situated in levels 3 and 4 for the posttest was higher in the experimental group compared with the control group (Fig. 3B). Results showing representa-
A comparison of posttest scores between the experimental and control group demonstrated that AR increases the complexity levels of students’ drawings of the augmented reality (AR).

Fig. 3. Percentage of student in each level of complexity learning, according to the drawing analyzed in the pretest and posttest, in the experimental group (A) and the control group (B). Comparison between pretest and posttest in the control group (without AR) was not found to be significant. In the experimental group, as judged by a higher number of students classified in level 3 after posttest.

Finally, the number of students in the experimental group classified in level 4 increased 9% after AR activities compared with 3% in the pretest. No students reached level 4 in the control group. Although no students were classified in level 4 in the control group for the pretest, 3% of the students of the experimental group was classified in level 4.

Table 4. Impact of the learning activity in the final exam of endocrine and neurophysiology chapters

| Chapter                     | Experimental Group | Control Group | P Value |
|-----------------------------|--------------------|---------------|---------|
| Neurophysiology             |                    |               |         |
| Women                       | 4.8 ± 0.1          | 4.8 ± 0.2     | NS      |
| Men                         | 4.9 ± 0.1          | 4.8 ± 0.1     | NS      |
| Endocrine                   |                    |               |         |
| Women                       | 4.6 ± 0.2          | 4.6 ± 0.2     | NS      |
| Men                         | 4.6 ± 0.1          | 4.7 ± 0.2     | NS      |

Values are student scores. No significant (NS) differences were found in the students’ performances in the other chapters of the physiology course. The final exam used a multiple-choice (a–d) questionnaire format. We compared the scores of the experimental group and control group, which ranged from 1 to 7, according to the academic grading in Chile, where 1.0–1.9 is very deficient; 2.0–2.9 is deficient; 3.0–3.9 is less than sufficient; 4.0–4.9 is sufficient; 5.0–5.9 is good; and 6.0–7.0 is outstanding. Final exam scores do not show significant differences when analyzing by gender.
The final exam covered aspects of heart anatomy, physiology of heart contraction, and molecular aspects of the cardiac cycle. The final exam used a multiple-choice (a–d) questionnaire format. We compared the scores of the experimental group and control group, which ranged from 1 to 7, according to the academic grading in Chile, where 1.0–1.9 is very deficient; 2.0–2.9 is deficient; 3.0–3.9 is less than sufficient; 4.0–4.9 is sufficient; 5.0–5.9 is good; and 6.0–7.0 is outstanding. The experimental group showed a significant increase in final exam scores in total. This effect was also observed by gender.

Along with level 4 representations, students also displayed capabilities toward the other representational levels, for example, explaining the process of cardiac contraction, labeling anatomical sections of the heart, and also including physiological variables and external influences. At level 4, students were able to use formal representations from anatomical (macro-structures) to biochemical processes, including, for example, molecules of CO₂, O₂, or Na⁺ and Ca²⁺ ions transported through the cell membrane and their relationship to the breathing process and exercise. The development of this last level allowed students to use representations to explain phenomena, solve problems, and make predictions.

Students performed better on the final evaluation of heart physiology content. To test the effect of our innovation, we used the final exam results for the heart physiology chapters of the physiology course, which was given to both the experimental and control groups of undergraduate students. The final exam includes aspects of heart anatomy, physiology of heart contraction, and molecular aspects of the cardiac cycle. The test consists of a 40-question questionnaire using multiple choice (a–d). We compared the scores of the experimental group and control group, which ranged from 1 to 7, according to the academic grading system in Chile (explained above). The experimental group showed a significant increase in the score of the final exam of cardiac function. This effect was also observed by gender (Table 5).

Learning sequence using AR and the activities increased motivation for lectures. A learning sequence is an ordering of student’s learning activities. In our AR activity, the learning sequence was based on activities guided by instructions printed in a small handbook with QR codes that can be scanned by smartphones and tablets to launch each activity of the AR sequence. An online survey was applied at the end of the semester, and 16 students voluntarily participated. When students were asked about the learning methodology, they reported high levels of motivation (Table 6). This was evidenced by students’ pre- and posttest results (Fig. 3), drawings, and their progression toward level 2 representations. These results indicate that an AR intervention helps to incorporate additional representational elements. Students also agreed that both the AR experiences and activities performed in the book of activities increased the motivation for the lectures and helped them to learn the content associated with the classes. Finally, 87.5% of students agreed or strongly agreed (statement C) that SPECTO should be further used in other anatomy and physiology lessons (Table 6).

### DISCUSSION

The results of this study demonstrate that students who participated in the experimental group reached higher comprehension and performed better on integration of processes and mechanisms related to cardiac contraction. This suggests that learning cardiac anatomy function via AR is more successful than by following a conventional teaching methodology, which is centered on textbooks, PowerPoint images, and teacher lectures, where the emphasis is focused on remembering and reproducing mechanisms or structures. When students were first asked to represent the phenomena of cardiac contraction, they designed representations based solely on physical characteristics. We found substantial differences in the frequency distribution of students’ levels for pre- and posttests in the experimental group, but not in the control group, despite both of them showing the same capability and scores in the pretest (Fig. 2).

Regarding the extent to which the promotion of visualization via AR sequences optimizes the learning experiences of students, we found that, in the short term (i.e., posttest results), the promotion of visualization using AR experiences was improved in the experimental group compared with the control group. Regarding the levels of learning, the observed increase achieved by the experimental group can be attributed, in part, to the fact that learning becomes increasingly active under the employed methodology (Fig. 4). By interacting with AR, students relate the abstract processes with a familiar visual-spatial language (19). The methodology tested with the experimental group favors the development of mental representations. Findings from this study also suggest that offering more

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**Table 5. Impact of the learning activity exploring heart contraction mechanisms using augmented reality on final exam scores for the heart physiology chapters of the physiology course for undergraduate students**

| Statements                                                                 | Experimental Group | Control Group | P Value |
|---------------------------------------------------------------------------|--------------------|---------------|---------|
| A. The learning methodology (augmented reality) has increased my motivation for the lectures. | 4.6 ± 0.1          | 4.0 ± 0.1     | <0.01   |
| B. The learning activities in which augmented reality was used have helped me learn course content. | 4.5 ± 0.1          | 4.1 ± 0.2     | <0.05   |
| C. The material used in the course (augmented reality) is well designed: it resembles reality. | 4.6 ± 0.1          | 4.1 ± 0.2     | <0.01   |
| D. I recommend this teaching methodology in other future anatomy lectures. | 4.6 ± 0.1          | 4.1 ± 0.2     | <0.01   |

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**Table 6. Survey results from students about their appreciation of this teaching-learning method**

| Statements                                                                 | 1 (6.25) | 2 (12.50) | 3 (18.75) | 4 (25.00) |
|---------------------------------------------------------------------------|----------|-----------|-----------|-----------|
| A. The learning methodology (augmented reality) has increased my motivation for the lectures. | 2 (12.50) | 7 (43.5)  | 7 (43.5)  |
| B. The learning activities in which augmented reality was used have helped me learn course content. | 1 (6.25)  | 3 (18.75) | 12 (75.0) |
| C. The material used in the course (augmented reality) is well designed: it resembles reality. | 1 (6.25)  | 1 (6.25)  | 6 (37.50) | 8 (50.0)  |
| D. I recommend this teaching methodology in other future anatomy lectures. | 1 (6.25)  | 2 (12.50) | 13 (81.25)|

Values are the no. of responses (with percentage in parentheses). 1 = Totally disagree; 2 = disagree; 3 = agree; 4 = totally agree.
comprehensive visual representations promotes a better scenario for learning physiology content. This was evidenced by the results observed in the final exam of heart physiology, demonstrating that the experimental group showed a significant increase in score levels (Table 5). Our results are consistent with other studies using AR. For example, Küçüklü et al. (14) used AR to improve students’ comprehension of the nervous system. They found that students’ achievements improved, and that students felt a reduced cognitive load, which in turn was conducive to higher graduation rates. In this study, AR gave students an immersive sensory experience by integrating digital data with anatomical structures (2).

Although it has been suggested that gender differences must be taken into consideration when developing educational tools (31), some previous game-based learning studies found no differences in outcomes related to gender (12, 28). Other studies investigating the influences on children’s visual cognition capabilities through playing with “intelligent matrix” with AR showed no difference by gender in performance (8). Robertson (31) found that female students had better retention of information than males because they use more time to write dialogues in the activity. Hsu (9) found that male and female students had similarly high learning effectiveness when using AR. This suggests that the human factor of gender seems not to have such a remarkable impact on learning effectiveness. Other personal characteristics, such as learning style or cognitive traits, could be taken into account in future studies (9). In support of these findings, we did not observe significant differences in the scores at final exam between women and men (Table 5).

The use of AR explains the macro- and microstructures, along with the molecular mechanisms of cardiac function, using high-definition images of a real cadaveric heart. This highly intuitive interface complements traditional classes, an aspect that has been reported by other authors (2, 20). Cadaveric dissection has been an important part of traditional education and the gold standard in gross anatomy. Our contribution is also to present the development of SPECTO, a complementary tool for the learning of anatomy and cardiac function. The value of this technology is that it allows for the creation of an interface that effectively meets curricular objectives.

Limitations of this study. The strength of agreement analyzed by Cohen’s kappa index showed medium strength for pretest and high for posttest in the experimental group, but high for pretest and high for posttest in the control group. In this regard, we believe that emotional and motivational situations might be present at the moment of the posttest in both control and experimental groups affecting our results. Another limitation of this study was the inability of our application to move subtly from the macroanatomical and microanatomical aspects,
directly to the molecular mechanisms of cardiac contraction. Although a high level of understanding was observed in the experimental student population, the chemical and molecular aspects were not fully integrated. The understanding of cellular processes and systemic physiology, together with their biomolecular aspects, is one of the keys to understanding the cardiac contraction cycle. We hope to develop new strategies for teaching other concepts, such as pathophysiology, to enhance student learning with an adjustable system of visualization. Our methodology is of interest for clinical, biomedical, and biochemistry teaching. For example, it can be conducive to explaining the multiple concepts of cardiac physiopathology.

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[References are not provided in the given text.]

AUTHOR CONTRIBUTIONS

A.A.G., P.A.L., S.P., and C.M. conceived and designed research; A.A.G., P.A.L., S.P., and C.M. performed experiments; A.A.G., P.A.L., S.P., B.G.M., and C.M. analyzed data; A.A.G., P.A.L., S.P., B.G.M., and C.M. interpreted results of experiments; A.A.G., P.A.L., S.P., and C.M. prepared figures; A.A.G., P.A.L., S.P., and C.M. drafted manuscript; A.A.G., P.A.L., S.P., and C.M. edited and revised manuscript; A.A.G., P.A.L., S.P., and C.M. approved final version of manuscript.

DISCLOSURES

No conflicts of interest, financial or otherwise, are declared by the authors.

AUTHOR CONTRIBUTIONS

A.A.G., P.A.L., S.P., and C.M. conceived and designed research; A.A.G., P.A.L., S.P., B.G.M., and C.M. performed experiments; A.A.G., P.A.L., S.P., and C.M. analyzed data; A.A.G., P.A.L., S.P., B.G.M., and C.M. interpreted results of experiments; A.A.G., P.A.L., S.P., and C.M. prepared figures; A.A.G., P.A.L., S.P., and C.M. drafted manuscript; A.A.G., P.A.L., S.P., and C.M. edited and revised manuscript; A.A.G., P.A.L., S.P., and C.M. approved final version of manuscript.

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