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LETTER

Knowledge maps as a complementary tool to learn and teach surgical anatomy in virtual reality: A case study in dental implantology

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Abstract

A thorough understanding of surgical anatomy is essential for preparing and training medical students to become competent and skilled surgeons. While Virtual Reality (VR) has shown to be a suitable interaction paradigm for surgical training, traditional anatomical VR models often rely on simple labels and arrows pointing to relevant landmarks. Yet, studies have indicated that such visual settings could benefit from knowledge maps as such representations explicitly illustrate the conceptual connections between anatomical landmarks. In this article, a VR educational tool is presented designed to explore the potential of knowledge maps as a complementary visual encoding for labeled 3D anatomy models. Focusing on surgical anatomy for implantology, it was investigated whether integrating knowledge maps within a VR environment could improve students' understanding and retention of complex anatomical relationships. The study involved 30 master's students in dentistry and 3 anatomy teachers, who used the tool and were subsequently assessed through surgical anatomy quizzes (measuring both completion times and scores) and subjective feedback (assessing user satisfaction, preferences, system usability, and task workload). The results showed that using knowledge maps in an immersive environment facilitates learning and teaching surgical anatomy applied to implantology, serving as a complementary tool to conventional VR educational methods.

1 | INTRODUCTION

A comprehensive understanding of anatomy is essential for all healthcare disciplines, but it is particularly crucial in surgical fields where precise knowledge of anatomical structures, their variations, and their relationships is fundamental for safe and effective procedures [1, 2]. In dental implantology, for example, a thorough grasp of oral anatomy—including relevant muscles, blood supply, and nerves—is critical for surgeons to navigate the complexities of implant placement confidently and safely [3]. Complications arising from injuries to these anatomical structures during surgery can lead to serious consequences [4, 5], highlighting the importance of having a deep understanding of both descriptive and topographic anatomy to prevent such outcomes [6, 7]. However, the sheer volume and complexity of anatomical information, coupled with the intricate interconnections between anatomical concepts, presents a significant challenge for students training and practicing to be medical professionals [8–10].

VR in anatomy education resorts on 3D anatomical models that are populated with labels (i.e. textual identifiers) and arrows pointing to relevant topographic landmarks within an anatomical structure. While this linear mapping between textual and visual information is highly relevant when learning and teaching anatomy, it poses significant challenges. Specifically, it is difficult to process this information due to the large amount of textual-visual relations that need to be memorized in a short amount of time. Moreover, since conventional labeling only serves to pinpoint anatomical landmarks, the reader must perform the cognitive load to build a knowledge map whose nodes and edges represent all the anatomical landmarks and their topological relationships [11].

Labeled anatomical data can be translated into knowledge representations, more specifically, knowledge maps in the form of Directed Acyclic Graphs (DAGs) [11] or, in more popular terms, a mind map [12–14]. Such representations allow students and teachers to build mental models using "general to particular reasoning": starting with a main concept as the root of the map (i.e. the main anatomical structure), it branches into several concepts (i.e. anatomical landmarks) that can branch into even smaller concepts, and so forth. This generates an easily readable hierarchy of concepts, facilitating the understanding of topological relationships among anatomical landmarks [11, 13] or anatomical variations [15]. This type of knowledge representation presents seemingly attractive features for both anatomy lecturers and students, as they encode anatomical knowledge in a more visual manner, explicitly revealing topological relationships. Such knowledge representations that express hierarchical relations between anatomical concepts are here named "anatomy maps".

Several studies have explored using DAGs as knowledge representations in VR, revealing that such DAGs facilitate conceptual understanding and retention [16–18]. However, these examples do not rely on DAGs applied in a VR anatomy education context, much less centered on VR for dental implantology education [19–22]. This current state of affairs clearly indicates that there exists a missed opportunity in using anatomy maps in such settings. Our study serves as a significant stepping stone in this area, particularly because the influence of VR knowledge maps on surgical anatomical learning remains largely unexplored. In this work, we evaluate the potential that anatomy maps in VR can bring to current surgical anatomy educational settings. We aim to determine whether these VR anatomy maps can improve the learning and perception of anatomical structures and their topological relationships, thereby addressing the educational needs of dental surgery. The insights gained from this study are valuable not only for the broader VR education community but also for those focused on the teaching-learning process of anatomy concepts.

We address the following research questions: **(RQ1)** Are VR anatomy maps a complementary approach to conventional VR educational materials for learning and teaching surgical anatomy? **(RQ2)** Can VR anatomy maps facilitate the learning and perception of anatomical structures and understanding of their topological relations? **(RQ3)** What are the benefits and limitations of VR anatomy maps in dental implant anatomy education?

The contribution of our work lies in the development and evaluation of a VR educational tool for anatomy instruction, specifically designed to enhance surgical training by leveraging the potential of VR anatomy maps. This tool features two types of labeled anatomy data representations: (i) 3D model with conventional labeling; and (ii) 3D model with conventional labeling together with an anatomy map framed inside a floating panel. Without loss of generality, we considered dental students and anatomy teachers as target users and, contentwise, we adopted a Topographic Anatomy textbook as source material that is used to learn and teach in a dental implantology course [23]. To develop this tool, we conducted interviews and co-design sessions with dental students and anatomy teachers. To assess the tool's effectiveness, we conducted two user studies: one involving 30 master's students in dentistry, who were evaluated through anatomical quizzes (measuring completion times and scores) and subjective feedback (assessing user satisfaction, preferences, system usability, and task workload), and another involving 3 anatomy teachers who provided subjective feedback on the tool's educational value and usability.

2 | RELATED WORK

Interactive anatomy education systems heavily rely on visual content consisting of medical illustrations and 3D models [24]. However, these contents alone are not sufficient to support the learning processes as users must correlate visual elements (e.g. topographic location and topological relationships of anatomical landmarks) with symbolic knowledge (e.g. names, concepts, functions of anatomical structures and the diverse relations between them) [25]. Therefore, more abstract representations that encode anatomical knowledge is a real and effective need throughout the education process [11].

Knowledge representations such as DAGs have been applied to digital anatomy education but were scantily used in practice [11, 26, 27], with the exception of tree-like structures such as vessels, nerves, and respiratory tract as these naturally resemble mind maps on their own. One of the first studies was performed by Schubert et al. which proposed a semantic net, mapping label data to volumetric data for three-dimensional visualization of anatomical concepts [26]. Another similar concept for knowledge representation was proposed by Brinkley et al. in their Digital Anatomist Program, a software framework for organizing, analyzing, visualizing, and utilizing biomedical information [27]. Knowledge graphs have also been utilized to encode anatomical variations allowing experts to compare and explore variations on branching structures interactively [28]. Thus, the true pedagogical value of DAG representations in anatomical education has yet to be properly evaluated and their potential remains untapped, especially when we consider more contemporary educational mediums such as VR. In fact, conventional practices remain obstinately faithful to passive teaching approaches that, traditionally, rely on lengthy textbook materials and static medical illustrations, which are known to be tedious and tiresome [24].

In a complementary vein, several immersive analytics studies have focused on interface and interaction technique issues related to DAGs and knowledge maps, since VR is a spatial computing paradigm offering, virtually, infinite space to accommodate large data representations [29]. Yet, none explored the potential of knowledge maps to represent labeled anatomical data with direct applications in surgical anatomy education. VR has the potential to enhance knowledge mapping by leveraging 3D space to arrange complex information, a feature absent in 2D solutions. While VR knowledge mapping examples exist [30–33], none are specifically designed for anatomy education.

VR has been reported to be useful for medical education, in general, and anatomy education, in particular [24, 34–36]. Multiple studies underscore its effectiveness in enhancing learning outcomes and user preference compared to traditional 2D mediums [37]. For example, Codd and Choudhury [35] found that a 3D VR model for teaching forearm anatomy performed comparably to traditional methods like dissection and textbooks. Moro et al. [38] demonstrated that VR was equally effective as tablet-based learning for skull anatomy, but with the added benefit of increased student engagement. Maresky et al. [39] found that an immersive VR simulation of cardiac anatomy significantly improved participants' scores compared to traditional study methods. Moreover, Gloy et al. [34] developed an immersive VR anatomy atlas that outperformed textbooks regarding knowledge retention.

Beyond anatomy education, VR has also shown significant promise in dental surgical training, providing realistic simulations that enable practitioners to practice and refine techniques in a controlled, risk-free environment [40, 41]. Ayoub and Pulijala [40] highlighted VR's utility in various aspects of oral and maxillofacial surgery, including enhancing surgical planning, improving training outcomes, and providing a more interactive and immersive learning experience, particularly in complex procedures like dental implantology. Likewise, Moussa et al. [41] emphasized the positive impact of VR in dental education, noting its potential to significantly enhance both clinical skills and theoretical knowledge, especially in fields like implantology.

Existing VR tools for anatomy education excel at presenting 3D visualizations of anatomical structures but they often lack a structured way of linking these visual representations with the corresponding textual and conceptual information (e.g. names, functions, relationships) that students need to fully understand anatomy [34, 35, 37–39]. Knowledge representations, such DAGs, while explored in some digital anatomy contexts, have not been fully leveraged within VR environments to their full potential [11, 26, 27]. Our work addresses this gap by introducing and evaluating a novel VR tool that incorporates anatomy maps (a type of DAG) to facilitate teaching and learning surgical anatomy.

3 | REQUIREMENTS GATHERING

3.1 | Interview sessions

During a span of two days, we conducted a series of interviews next to two experienced anatomy teachers, each holding a Ph.D. in Dentistry, 58 and 61 years old, respectively. Additionally, we engaged 16 M.Sc. students currently pursuing Dentistry degrees, ranging in age from 21 to 29. Among the participants, both teachers were male, while there were 6 male and 10 female students. To ensure ethical compliance and participation, all interviewees completed an informed consent form along with a demographic profile questionnaire. These semi-structured interviews played a pivotal role in eliciting valuable insights and gathering user requirements. They covered a wide spectrum of topics, encompassing the teaching methodologies employed by the instructors, the evaluation processes utilized in assessing students, as well as the study methods adopted by dental students themselves. Furthermore, the interviews included discussions on their feedback and perspectives regarding anatomy classes.

Teachers' interviews - The teachers' interview was divided into four different types of questions: *Conventional Teaching and Learning Tasks*, *"Out of the Box" Tasks*, *Knowledge Assessment Methods*, and *Virtual Reality as a Learning and Education Method*. For the first two types of questions, the teachers responded that their practice relies on common teaching tools and activities such as PowerPoint presentations, typical 2D labeled medical illustrations, videos, and physical models. Both answered that they do not use *"Out of the Box"* methods to teach. Regarding *Knowledge Assessment Methods*, the interviewed teachers evaluate students through oral and written assessments. When questioned about *Virtual Reality as a Learning and Education Method*, both teachers expressed curiosity and even motivation to use VR tools in their teaching practices, yet none of them ever used such technology.

Students' interviews - In this case, the interview was divided into two types of questions: *Study and Learning Methods*, and *Lecturing Methods*. For the first type of questions, students provided information about their study methods that, without surprise, relied on PowerPoint slides, textbooks, pictures, and online material. Yet, several students elaborate handwritten notes accompanied by hand-drawn sketches of anatomical structures with labels and, remarkably, even diagrams that consist of true DAGs of anatomical landmarks or concepts, especially when the anatomical content has a tree-like structure such as vessels, nerves, and respiratory tract as these naturally resemble mind maps on their own. Interviewed students reported that the major challenge while studying anatomy was the vast amount of concepts and their relations, making it very difficult to memorize.

As for *Lecturing Methods*, students mentioned that most anatomy lectures heavily depended on PowerPoint slides with a lot of textual content instead of visual information; while during practical classes, the lecturers swamped them with too many anatomical details to memorize in each lesson. Interviewed students consider that excessive amounts of textual and flat visual information could be combated if lectures adopted the inclusion of more interactive content, such as physical and digital anatomy models or videos.

One interviewed student explicitly mentioned the use of mind maps (as those famously created by Tony Buzan [12]) as a form of studying, namely to assist memorization and to summarize content. She started using this technique in high school to help her internalize concepts faster and to better understand hierarchies, and continued using this tool for her university-level courses. In particular, she makes extensive use of mind maps for her anatomy classes to memorize theoretical content. As for her process, she usually draws mind maps by hand that, in her own words, look like a spider web where the center consists of the main concept, while the first row of spokes form the "first level of a hierarchy" that, in turn, could branch out into other spokes, and so forth. Unfortunately, she did not have photographs nor original manuscripts of her mind maps because, at the time, she passed her study material to other colleagues, who passed them on to others. This indicates that such mind map materials were demanded by more students.

3.2 | Co-design sessions

Based on the interview sessions, several low/medium fidelity prototypes were built, namely, sketches, wireframes, and an early VR app. Then we organized several co-design sessions with a dental teacher (one of the co-authors) at [concealed for review] who had 4 years of teaching anatomy for Dentistry undergrads and post-grads enrolled in Dental Implantology. While he provided feedback about early low/medium fidelity prototypes, his role was pivotal for building and curating all anatomical contents that were included in the final prototype, while also providing vital input for all quizzes.

Most of the co-design sessions were focused on deciding the anatomical content, converting textual information from a textbook [25], building the anatomy maps, and defining the quiz materials. However, in one of the co-design sessions, a medium-fidelity prototype developed with Unity was demoed. The VR app mimicked a conventional VR anatomy map [42, 43]: it contained a 3D model (in our case, a mandible and a maxilla) in the center of the scene, scaled to be larger than in real life (in a 4:1 ratio), with conventional labels attached to landmarks that could be turned visible or not whenever touched. Each label was colored according to its system: grey represents osteology, blue represents muscles, red represents vascularization, purple represents veins, yellow represents innervations, and green for other types of systems. Feedback from the co-design participant turned out to be positive. The professional agreed that it was useful to have colors on the labels because it helps to identify the type of landmarks being selected. One suggestion was to really provide liberty of manipulation to the user and to allow the user to move around the 3D model.

4 | DESIGN AND IMPLEMENTATION OF IMPLANTIGRAPH

Based on the interviews and co-design sessions, we developed a high-fidelity prototype called IMPLANTIGRAPH to address the benefits and limitations of VR anatomy maps for surgical anatomy in the context of dental education.

4.1 | Anatomical content

The source material of textual content to build the anatomy maps was retrieved from a textbook of Topographic Anatomy textbook [23], which is used as source material in a dental implantology course at [concealed for review]. At first, we divided the maxilla and the mandible into eight different regions: right and left posterior and anterior segments for both structures. Given that we did not consider any type of anatomical variations, we simplified the regions into four key areas: the posterior and anterior maxilla, and the posterior and anterior mandible. Each of these 4 areas are candidate center nodes of an anatomy map that will contain sub-areas as inner nodes and anatomical landmarks as leaves (Figure 1).

4.2 | 3D models

A patient-specific 3D model of parts of a skull was considered the centerpiece of the VR scenes. The model is available at the Open-Full-Jaw Dataset Repository that consists of an open-access data set of 17 patient-specific textureless STL models of human jaws. We selected *model 13* since it was the most complete of the set. The 3D model was then imported into Blender (version 3.3. LTS) and the mesh was divided into two separate 3D models, one with the mandible part (Figure 2) and another with the maxilla part (Figure 3). To add realism, a procedural bone texture was created using the Blender. The models were then exported as an FBX file and imported into Unity (version 2021.3.8f1).

4.3 | Interaction

To manipulate the 3D model, the user can use the left thumbstick for planar translation (parallel to the ground level) and the right thumbstick to trigger horizontal or vertical rotation. Users can interact with the labels (Figure 3), either those figuring on an anatomy map or as conventional labels on the 3D model. The conventional labels are clickable buttons on the model's surface (Figure 2), color-coded by constituent type and varying in shape to represent different anatomical features. When a conventional label is selected, a connected text box appears or disappears. Conventional labels are anchored to the 3D model, so, once the model moves in space the labels follow and always face towards the user's point of view.

The anatomy maps are represented as multiple colored label boxes connected with line segments, positioned to reflect the DAG hierarchy of the anatomical landmarks, which are framed inside a dark-background panel (Figure 3 - Bottom). The root node is the name for one of the main areas, which branches into system levels (e.g. Osteology, Muscles etc.), and, finally, is subdivided into different anatomical landmarks. The entire panel can be maneuvered in space through the controller's grab button, but constrained to a spherical dome so that the panel faces the user's point of view. Once a label on the anatomy map is selected, both the label box on the anatomy map and the corresponding conventional label text box are highlighted with more saturated colors.

5 | USER STUDIES

We performed two user studies to assess the potential of VR anatomy maps as a studying and teaching tool. We posit three hypotheses: **H1**: VR anatomy maps serve as a complementary approach to learning and teaching surgical anatomy,

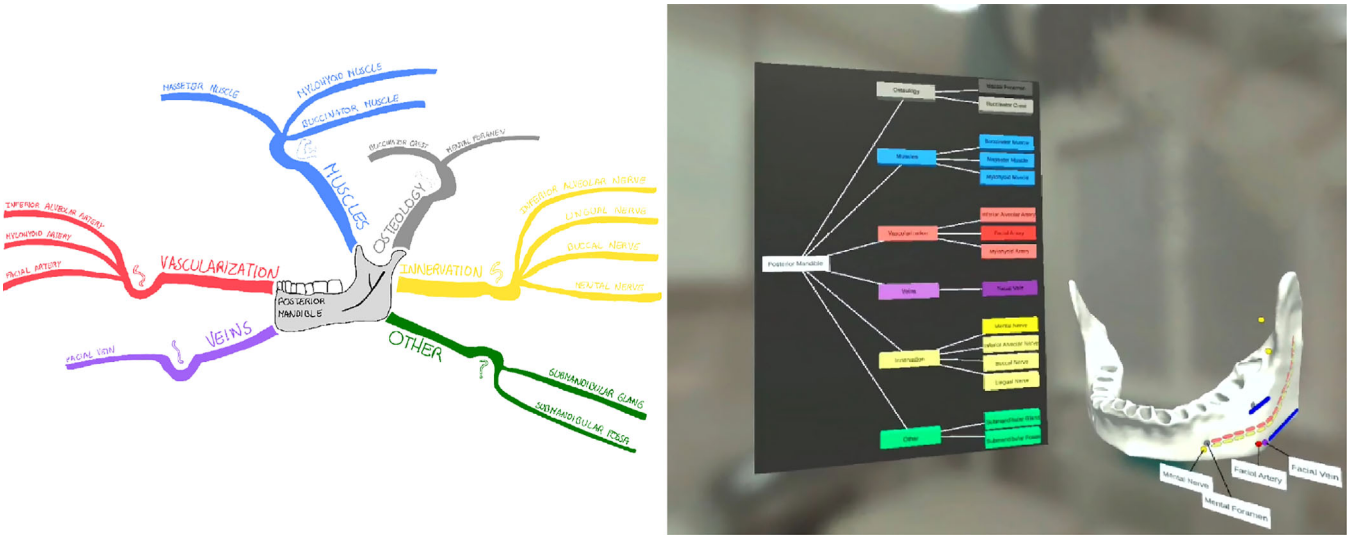

FIGURE 1 Left: Knowledge map of the Posterior Mandible illustrating the conceptual relationships between its anatomical landmarks. The rendering style is similar to the mind maps found in Tony Buzan's books [12]. Right: Knowledge Map Layout: virtual environment featuring a patient-specific 3D model with labels, accompanied by a knowledge map placed next to the anatomical structure.

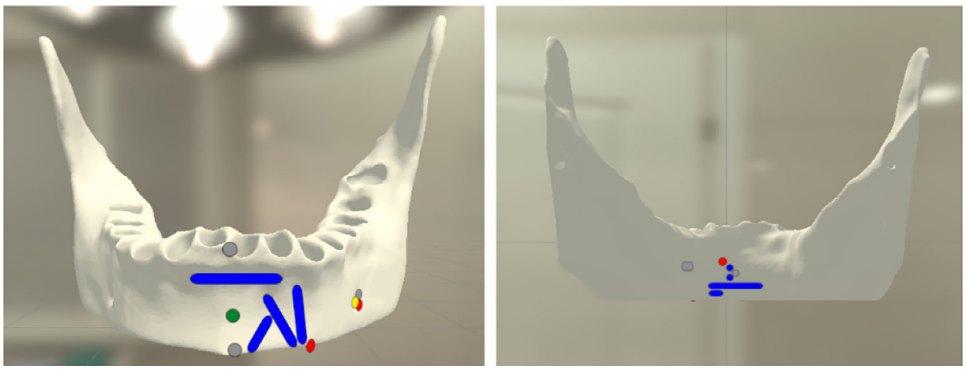

FIGURE 2 Left: Anterior frontal view of the mandible and its relevant landmarks. Right: Posterior view of the mandible and its relevant landmarks.

enhancing the educational experience compared to using solely conventional VR educational materials; **H2**: VR anatomy maps enhance users' abilities to perceive and comprehend anatomical structures and their spatial relationships, thereby facilitating deeper learning outcomes such as higher quiz scores, and faster quiz completion times; and **H3**: Users will express higher satisfaction, preference, and perceived usability, and report reduced task workload when using VR anatomy maps in dental implant anatomy education compared to traditional VR methods.

5.1 | Participants

A total of 33 participants were invited to take part in our user study: 30 Master's students in Dentistry, and 3 anatomy teachers from [concealed for review]. None of these participants took part in the interviews or co-design sessions for the requirements-gathering phase. The first user study focused on the learning aspect of VR anatomy maps. Thirty students participated (20 female, 10 male), with ages ranging from 21 to 31 (Mean = 23.5, SD = 2.7), all enrolled in a Master's Degree in Dentistry, although one participant was also employed as an Oral Hygienist for 5 years. Of the 30 students, 9 of them said that they never dealt with virtual reality technology. The second user study focused on the teaching side of VR anatomy maps. The invited 3 teachers (all male), with years of experience ranging between 2 and 25 (Mean = 10.7, SD = 10.2), two of whom have a Post-Graduate Degree in Dentistry and one a Ph.D. Degree in Dentistry. They are all employed with dental specialties such as *Implantology*, *Oral Rehabilitation and Implantology*, and *Oral Pathology and Surgery (with a subspecialty in Oral Cancer)*. One of the professors never dealt with virtual reality technology.

5.2 | Apparatus

The IMPLANTIGRAPH app was developed in Unity (version 2021.3.8f1) and ran on the Oculus Quest 1, configured for the

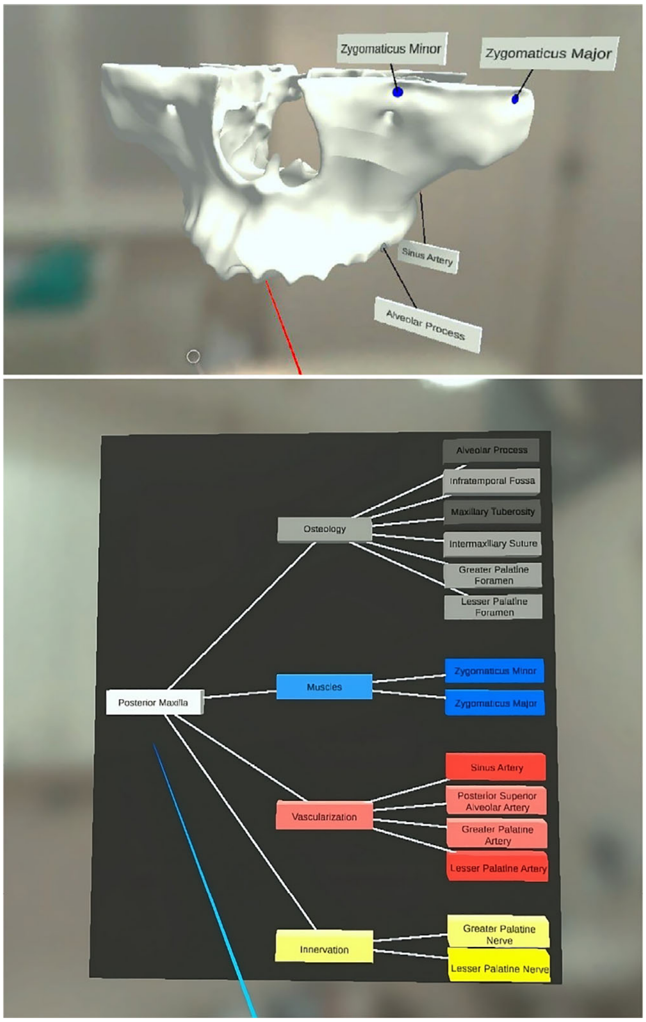

FIGURE 3 Top: Conventional labels of the posterior maxilla. Bottom: Anatomy map of the posterior maxilla.

FIGURE 4 Student participating in the User Study while interacting with IMPLANTIGRAPH.

seated position (Figure 4). Both user studies took place at a clinical setting located at [concealed for review]. The setup consisted of an Oculus Quest 1 headset and two portable computers, one to support the casting of the VR headset viewpoint and another to fill in the questionnaires and answer quizzes.

5.3 | Variables

Two independent variables were chosen to evaluate the potential of anatomy maps in VR: (i) the *the layout of anatomical information*: conventional labels (as our baseline) vs. conventional labels accompanied by a VR anatomy map and (ii) *task complexity*, defined by the number of leaf nodes in each anatomy map, which corresponds to the number of anatomical concepts to learn. Regarding the *task complexity*, we considered 3 different anatomical contents with levels of complexity ranging from easy - medium - hard (i.e. the more concepts and, consequently, the number of relations portrayed in an anatomy map, the harder it is to learn). The dependent variables considered included both objective measures (quiz completion times and quiz scores) and subjective measures (satisfaction, preferences regarding the layouts, perceived usability and task workload). For the user study that involved teachers, we did not evaluate any of the objective measures, since we were interested only in their qualitative feedback as experts in the field.

5.4 | Tasks

For the user study with students, we included a habituation task focused on the anterior mandible to familiarize them with the IMPLANTIGRAPH interface and its features. Following this, students completed three tasks, each focused on a different anatomical region and reflecting varying levels of difficulty based on the number of anatomical concepts (i.e. leaf nodes and their relationships) within the anatomy map: Task 1: Posterior Maxilla (Figure 5 - Left) had 14 nodes, Task 2: Anterior Mandible (Figure 5 - Middle) had 18 nodes, and Task 3: Anterior Maxilla (Figure 5 - Right) had 24 nodes, making it the most complex. Each task started with a 5-min study phase, during which participants explored the assigned anatomical region using IMPLANTIGRAPH, focusing on memorizing the anatomical concepts presented in the task. This was followed by an evaluation phase where participants completed a 3-question quiz per task, assessing their ability to recall and identify the anatomical structures and relationships relevant to the task. The study with teachers did not include a quiz evaluation. Instead, teachers were given a free-hands session to explore all features of IMPLANTIGRAPH without specific tasks or assessments.

5.5 | Procedure

For the evaluation method of the Master students' user study, we considered a between-group design. Students were equally divided into Group A (conventional labels, our baseline) and Group B (3D anatomical model with conventional labels

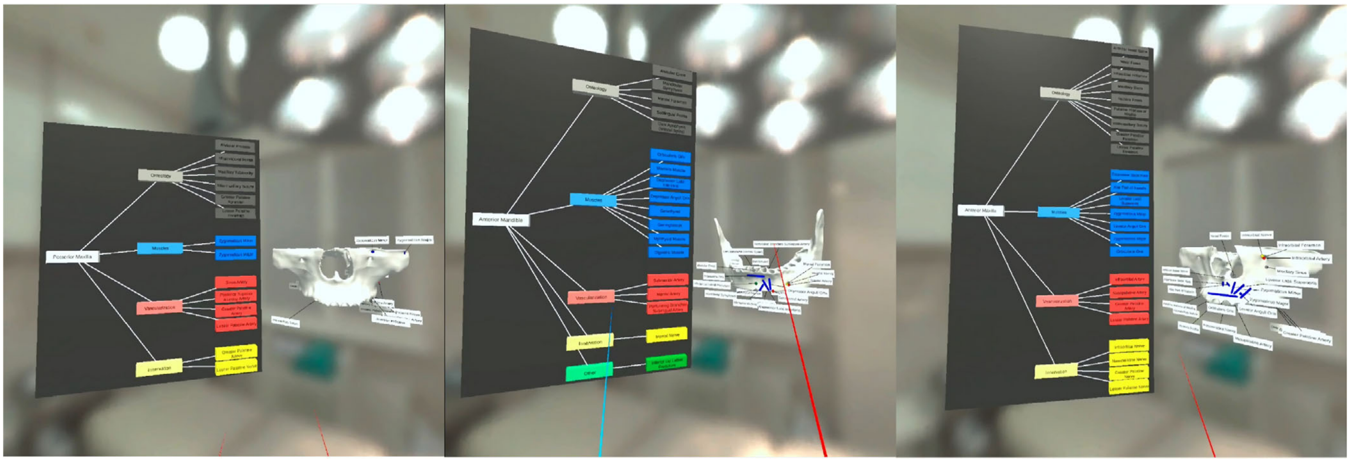

FIGURE 5 (Left) Task 1: Posterior Maxilla. Middle Task 2: Anterior Mandible. (Right) Task 3: Anterior Maxilla. The conventional labels were enabled simultaneously to illustrate the complexity of the tasks. In the VR environment, these labels can appear individually according to users interaction with the landmarks on the 3D model.

accompanied by a VR anatomy map). Teachers tested both *layout* conditions. At the beginning of each session, each participant was asked to fill in an informed consent form to explain the key elements of the study and what their participation will involve, and a demographic profile form regarding their gender, education, employment (if applies), and previous VR experience, followed by a quick explanation of the structure of the session and a demonstration on how the prototype works. The students were first asked to perform a habituation task (up to 5 min), consisting of a brief guided exploration of the VR environment and interaction with the basic functionalities of IMPLANTIGRAPH. Then, they were given a sequence of 3 tasks, randomized using the Latin Squares method, each divided into a study phase (taking up to 5 min) and, then, an evaluation phase where they had to complete a 3-question quiz. Quiz score and time of completion were measured. As for the teachers' user study, they were invited to freely explore IMPLANTIGRAPH, with and without anatomy maps, for a maximum time of 10 min.

At the end of each session, participants were directed to complete a User Satisfaction Questionnaire (to receive feedback on the *layouts* and the user's preferences), a SUS questionnaire [44] (to measure the usability of the prototype) and a NASA-TLX questionnaire [45] (to assess the task's work-load). Lastly, the participants were submitted to a semi-structured interview regarding the use of anatomical maps in VR, the advantages and disadvantages of using this prototype, and what changes they would suggest to improve the application. A full session lasted between 40 and 50 min with the students and 20 to 30 min with the teachers.

6 | RESULTS AND DISCUSSION

To access the learning aspects of VR anatomy maps, we performed statistical analysis upon the metrics from the students' user study, which were all carried out using IBM SPSS Statistics 26 [46] for Windows. For all inference statistics tests considered (i.e. Shapiro-Wilk Test, Independent Samples t-Test, Chi-square Test, One-Sample Wilcoxon Signed Tank Test, and Mann-Whitney U Test), a p-value of less than $alpha = 0{,}05$ was assumed as statistically significant. Concerning the user study with anatomy teachers, since we only had 3 experts involved, there was no need to perform a thorough statistical analysis. To interpret the SUS questionnaire, we computed a unique number that represents a composite measure of the overall usability of the system [44]. To calculate the NASA-TLX questionnaire, we calculated unweighted scores between 0 and 100 from a 21-item Likert scale [45] and assigned those values to a specific workload classification. [47]. Finally, the subjective data gathered from the semi-structured interviews with both students and teachers was analyzed through a thematic analysis method.

6.1 | Quizzes completion time

The time students needed to complete the quizzes gave us some insights into whether anatomy maps help to answer quizzes more or less rapidly. The distribution of times to complete each quiz by both groups is represented in Figure 6. The distributions of the quiz completion times were tested for normal distribution using the Shapiro-Wilk Test. Two out of the six p-values were less than 0,05, so the assumption of normality was violated; however, the descriptive analysis showed that the characteristics of the data (*skewness* and *kurtosis* values [48]) allowed us to use parametric tests. We performed an Independent Samples t-Test with the null hypothesis (H0) defined as "The means of the quizzes completion times by resorting or not on VR anatomy maps are identical".

Based on the descriptive statistics, Figure 6 shows that the quiz completion time is slightly higher when anatomy maps are part of the study phase. This result can be justified either by a longer time to mentally memorize/revive the concepts or to

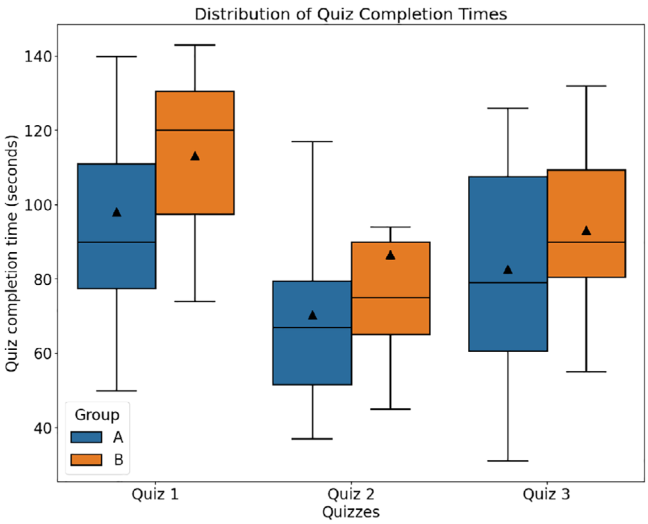

FIGURE 6 Quiz completion time (in seconds) for each quiz, comparing Group A and Group B.

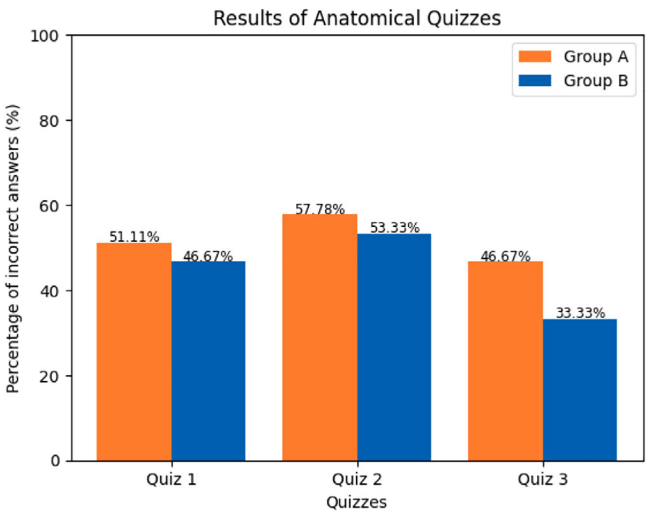

FIGURE 7 Percentage of incorrect answers per quiz, comparing Group A and Group B.

construct a mind map that mentally organizes the anatomical information. Although Group B took more time answering the quizzes, the p-values from the t-tests are all above the alpha level of 0.05 (Quiz 1: $p = 0.214$, Quiz 2: $p = 0.157$, Quiz 3: $p = 0.292$). Thus, we did not find statistically significant differences in the average quiz completion time between Groups A and B.

6.2 | Quizzes scores

The results of the anatomical quizzes allowed us to assess whether the use of anatomy maps inside an immersive 3D environment has the potential to be a study tool. For each group, we compared the percentage of incorrect answers for each question per quiz for Group A and Group B, as shown in Figure 7. These metric samples are independent, so we did not need to test normality: we used a non-parametric test [49], the Chi-square Test with the null hypothesis (H0) defined as "The percentage of incorrect answers for each question per quiz by resorting or not on VR anatomy maps are identical".

Analyzing each of the 9 questions, Group A had more incorrect answers (5 incorrectly answered questions) than Group B (3 incorrectly answered questions). Figure 7 shows that the percentage difference from each group between each quiz is, respectively, 4,44%, 4,45%, and 13,34%. Taking into account that the difficulty increases with the quiz (Quiz 1 is the easiest and Quiz 3 is the most difficult) and that the percentage differences increase as well, this indicates that Group B answered fewer incorrect answers and, therefore, the anatomical maps seemed to benefit the learning process. This goes along with Figure 7 which indicates that, overall, Group B had the best results (less percentage of incorrect answers). At last, the results from the Chi-square Test showed that only the third question of Quiz 3 was statistically significant, so overall, the results are inconclusive about the use of anatomy maps as a study VR tool, therefore the null hypothesis was accepted.

6.3 | User satisfaction and preferences

Participants were asked to fill in a User Satisfaction and Preference questionnaire. For the satisfaction questions, we performed the One-Sample Wilcoxon Signed Rank Test with the null hypothesis (H0) defined as "The median of each Likert item equals the hypothesized median (3.5)", and for the preference questions, we used descriptive statistics. Table 1 presents the median (Mdn) and interquartile range (IQR) of participant responses to the Likert items in the User Satisfaction questionnaire related to conventional labels, while Table 2 provides the corresponding information for anatomy maps.

Table 1 shows that all the medians were higher than 3,5, with low dispersion values (between 0 and 2) confirming that participants evaluated positively the 3D model with conventional labels. Table 2 proves that all medians were higher than 3,5, with low dispersion values (between 0 and 3), indicating that these participants also positively evaluated VR anatomy maps. The p-values from both tests are all less than *alpha*, meaning that the results are statistically significant.

For the preference questions, 13 out of 15 students in Group B preferred the conventional 3D model with conventional labels, and 11 out of 15 found it to be the most appealing. Among the teachers, 2 out of 3 preferred the 3D model with conventional labels, and all 3 found it to be the most appealing condition. From these results, we can conclude that both Group B and the teachers, in general, preferred the 3D model with conventional labels when compared to VR anatomy maps.

6.4 | System usability

Participants were asked to fill in a System Usability Scale (SUS) questionnaire to measure the perceived usability of

TABLE 1 Median (Mdn) and Interquartile Range (IQR) of the responses to the Likert items of the User Satisfaction questionnaire related to the Conventional Labels.

Statements	Group A Mdn (IQR)	Group B Mdn (IQR)	Teachers Mdn (IQR)
Helps locating elements anatomically.	6 (1)	6 (1)	6 (0)
Helps identifying different types of constituents.	6 (0)	5 (1)	6 (0)
Helps memorizing the constitution of the region.	5 (1)	6 (1)	6 (0)
Helps perceiving the anatomy of the region.	6 (1)	6 (1)	6 (0)
Are useful.	6 (0)	6 (1)	6 (0)
Are easy to use.	5 (1)	6 (1)	6 (0)
Help fast learning.	6 (1)	6 (1)	6 (0)
Are useful to study anatomy related to implantology.	6 (1)	6 (1)	6 (0)
Its interactivity promotes focus and learning.	6 (2)	6 (1)	6 (0)
Being able to move and rotate the 3D model is useful.	6 (0)	6 (0)	6 (0)

TABLE 2 Median (Mdn) and Interquartile Range (IQR) of the responses to the Likert items of the User Satisfaction questionnaire related to the Anatomy Map.

Statements	Group B Mdn (IQR)	Teachers Mdn (IQR)
Helps locating elements anatomically.	6 (3)	6 (0)
Helps identify the different types of constituents.	6 (2)	6 (0)
Helps memorize the constitution of the region.	5 (3)	6 (0)
Helps perceive the anatomy of the region.	6 (3)	5 (0)
Is useful.	6 (2)	6 (0)
Is easy to use.	6 (1)	6 (0)
Helps fast learning.	5 (1)	6 (0)
Is useful to study anatomy related to implantology.	5 (3)	6 (0)
Its interactivity promotes focus and learning.	5 (3)	6 (0)
Interaction of both layouts helps anatomical study of the region.	6 (1)	6 (0)
Being able to grab and move the anatomy map is useful.	6 (1)	6 (0)

TABLE 3 Means and Standard Deviation (SD) of each NASA-TLX parameter as well as the final NASA-TLX score for each group.

	Group A		Group B		Teachers	
NASA Parameters	Mean	SD	Mean	SD	Mean	SD
Mental demand	20,33	22,02	32,00	28,74	15,00	7,07
Physical demand	14,00	12,14	18,00	21,74	11,67	6,24
Temporal demand	24,33	23,08	34,00	32,62	13,33	8,50
Performance	16,00	22,08	15,67	24,28	28,33	33,25
Effort	19,67	18,48	30,00	31,30	21,67	16,50
Frustration	14,33	14,81	23,33	29,19	8,33	2,36
Final Score	18,11	18,78	25,50	27,98	16,39	12,32

IMPLANTIGRAPH. All SUS scores were above 68. The groups are independent, so we used a Mann-Whitney U Test with the null hypothesis (H0) defined as “The difference between the mean of the SUS score and the average score (68) is zero”. Group A’s mean score was 87.50 (SD = 8.06), Group B’s mean score was 87.83 (SD = 6.94), and Teachers’ mean score was 90 (SD = 7.36). Since the three means are above the average, we can conclude that participants perceived IMPLANTIGRAPH to have a good user interface and good usability. However, the results from the Mann-Whitney U Test showed all values of Z negative and all p-values bigger than *alpha*, so the results are not statistically significant.

6.5 | Perceived workload

For the NASA-TLX, we also performed a Mann-Whitney U Test with the null hypothesis (H0) defined as “The probability distribution of one group is the same as the probability distribution of the other group”. The mean score and SD of each parameter, as well as the final score, are presented in Table 3.

Table 3 shows that for Group A the majority of the means are in the “Very Low” range, only *Mental Demand* and *Temporal Demand* enter the next value of the scale; this could be due to the amount of information to study under the 5-min tasks. Group B has the majority in the “Low” range, with only *Physical Demand* and *Performance* in the “Very Low” range; Group B had the same information on two different layouts, so it could be overwhelming, leading to a bigger workload, hence the “Low” values; the “Very Low” values on *Physical Demand* and *Performance* demonstrates that using two layouts does not affect the experience. As for the Teachers, the majority are also in the “Very Low” range, with only the *Performance* and *Effort* located in the “Low” range. These results are quite different from the students. This could be due to teachers possibly having more difficulty in adapting to newer technology and having to make an extra effort to succeed. The final scores of each group are situated in the “Very Low” (two of them) and “Low” range, which means that IMPLANTIGRAPH is not considered to have high demand levels, being an easy-to-use study and teaching tool. The results from the Mann-Whitney U test revealed all Z-values negative and all p-values bigger than *alpha*, so the results can not be considered statistically significant.

6.6 | Verbal user's feedback

At the end of the sessions, participants were asked to answer questions to provide more detailed feedback related to IMPLANTIGRAPH, their advantages and disadvantages, and suggestions for further improvements.

Complement to conventional studying methods: All participants said that IMPLANTIGRAPH was a good complement to their studies. Group A stated that the information was *"easy to visualize and intuitive"* and the *"3D perspective is a more interactive way to learn"*. Group B had the same opinion regarding the prototype as a whole but considered VR anatomy maps *"less useful"* than the conventional 3D model with floating labels. Teachers said it is *"logical to have both types of content because anatomy maps complement the floating labels information"*.

Interaction and content benefit: Group A said that the 3D perspective of the conventional labels was *"better than using books"*, as they could see up close the *"exact locations by moving the model"*, and VR brought *"spatial visualization to a new level"*. Group B said that the *"interaction between anatomy maps and conventional labels is a good idea"*, the *"color scheme was a major help"*, and color code contributes to *"a better memorization and revision"*. Teachers said that *"anatomy maps ease memorization"* while being "*interactive and intuitive to understand*".

Limitations to the prototype: Some students from both groups said that *"some of the label boxes and landmarks when too close together, making it hard to interact with"*, *"using the prototype for an extensive period of time can be tiresome"*, and complained about *"the controllers' sensibility"*. One teacher complained that *"only the exterior surface of the bones were visible"*, there was no way to see *"intersections or change transparency"*.

Future acceptability: When asked if participants would use the prototype, all of them said *"yes"* to use it while studying anatomy, or to plan real surgeries.

6.7 | Insights and findings

Little is known about how VR knowledge maps influence surgical anatomy learning. Our proposed VR anatomy knowledge maps represent a novel approach in the VR community, specifically designed to advance surgical anatomy education. To our knowledge, our study is the first to indicate that VR anatomy maps provide improvements on student learning, particularly when dealing with complex anatomical content. Although most quantitative metrics (quizzes completion time, system usability and perceived workload) did not show statistically significant differences between groups, this indicates that VR anatomy maps do not adversely affect these factors. Therefore, VR anatomy maps are comparable to conventional VR methods regarding quiz completion time, system usability, and perceived workload. As for quiz scores, the results indicate that VR knowledge maps lead to a lesser number of incorrect answers and are beneficial for the most difficult task (learning a more complex anatomical structure). This aligns with the qualitative feedback, where participants generally found VKMs to be a useful, more interactive complement to traditional 3D labels, potentially aiding memorization. This contribution is particularly significant as it demonstrates that VR knowledge maps can be an effective and innovative tool in VR surgical training, enhancing the understanding and retention of complex anatomical structures. In surgery, where precise anatomical knowledge is critical, this tool can help better prepare surgeons, potentially leading to improved surgical outcomes. While participants did not explicitly indicate anatomy maps as a superior alternative to conventional 3D labels, they viewed anatomy maps as a valuable complementary approach, especially when dealing with a greater number of concepts (i.e. anatomical landmarks).

Despite these promising findings, our study has several limitations that need to be addressed. The small sample size limits the generalizability of our results, and the quizzes primarily assessed recall and identification rather than deeper understanding or application of anatomical knowledge. This focus may not fully capture the potential benefits of VR anatomy maps. Additionally, some participants reported technical issues with the prototype, such as overlapping labels and cumbersome controls. Future studies should involve larger sample sizes to validate our findings and investigate the impact of VR anatomy maps on a wider range of learning outcomes. Moreover, further development of the prototype is necessary to resolve the technical issues and optimize the user experience. Despite these challenges, our findings suggest that VR knowledge maps hold promise as a tool for enhancing conventional VR anatomical education.

7 | CONCLUSIONS AND FUTURE WORK

We explored the benefits, limitations, and viability of utilizing knowledge maps in VR for surgical anatomy education, with a specific focus on dental implant surgery. These VR anatomy maps offer a powerful visual representation connecting anatomical concepts, aiding in a deeper understanding of the complex relationships among various anatomical landmarks, which is crucial for the precision required in surgical procedures. Through interviews and co-design sessions involving dental students and anatomy teachers, an educational VR tool named IMPLANTIGRAPH was developed to be a learning and teaching tool for topographic anatomy applied to dental implantology. We then conducted a user study that included thirty Master's students in Dentistry and three teachers. Our findings suggest that VR anatomy maps, while not considered superior to conventional VR methods, do not negatively impact learning and can potentially enhance memorization and understanding, especially in complex anatomical areas, which is particularly important in dental surgery, where precise and accurate anatomical knowledge directly contributes to the safety and success of surgical procedures. This is supported by quantitative data (lesser number of incorrect answers and comparable quiz completion times, system usability, and perceived workload) and qualitative feedback (participants found VR anatomy maps to be a useful complement to traditional 3D labels). Overall, feedback from participants indicated a positive reception of anatomy maps as a beneficial tool for oral surgery education.

Finally, future enhancements were suggested by participants: (i) the addition of a filtering menu for anatomical landmarks by the system; (ii) collapsible anatomy maps for selective study; (iii) the ability to instantiate multiple collapsible anatomy maps in the 3D scene as individual post-its instead of having one large, single, full-blown anatomy map; and (iv) the option to create personalized anatomy maps from scratch. Overall, the study highlights the potential of knowledge maps in VR anatomy education, offering a valuable supplement to traditional VR methods for improved learning and teaching experiences.

AUTHOR CONTRIBUTIONS

Inês M. Lúcio: Data curation; formal analysis; investigation; writing—original draft. **Bernardo Faria**: Data curation; formal analysis; investigation; software; validation; visualization; writing—original draft. **Renata Raidou**: Conceptualization; investigation; methodology; project administration; supervision; writing—review and editing. **Luís Proença**: Data curation; formal analysis; validation; writing—review and editing. **Carlos Zagalo**: Conceptualization; resources. **José João Mendes**: Conceptualization; funding acquisition; project administration; resources. **Pedro Rodrigues**: Conceptualization; funding acquisition; investigation; methodology; project administration; resources; supervision; writing—original draft; writing—review and editing. **Daniel Simões Lopes**: Conceptualization; funding acquisition; investigation; methodology; project administration; resources; supervision; writing—original draft; writing—review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

Research data are not shared.

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