INSTITUTO UNIVERSITÁRIO EGAS MONIZ

DOUTORAMENTO EM CIÊNCIAS BIOMÉDICAS

DENTIFY: VIRTUAL REALITY AND HAPTICS IN TEACHING DENTAL IMPLANTOLOGY AND OPERATIVE DENTISTRY – AN APPROACH TO MULTIMODAL SIMULATION

Trabalho submetido por
Pedro Miguel da Silva Rodrigues
para a obtenção do grau de Doutor em Ciências Biomédicas

Trabalho orientado por
Prof. Doutor José João Baltazar Mendes

outubro de 2023

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DEDICATION

To my parents, Maria de Fátima Gonçalves da Silva and José Nascimento Rodrigues, for their unconditional love, dedication, altruism, support, teaching, kindness, humility, their absolute and relentless daily demonstration of happiness in each gesture and in each word, for all the things they had to give up on to allow for me and my brother to chase our dreams, which were, truly, their own dreams! For as far as I can remember (and I'm said to have a good memory), you both have always been the personification of dignity, integrity and generosity!

To my dearest mother: I love you dearly and keep teaching me how to be more like you!

To my beloved Father who I will always miss: I love you dearly and QNPVSC!

To my dearest younger brother, António Jorge da Silva Rodrigues for his undeniable friendship, inspiring sensibility, kindness, support and for allowing me to share my childhood, my teen years and my adult life with a person who integrates the best traits Humanity has to offer; you are an absolute example! For always being here, in this fragment of space and time to which I am privileged enough to call my life, just like Tom Sawyer and Huckleberry Finn.

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To all of us who share the Egas Moniz School of Health and Science DNA. Work Hard, Play Hard!

To Tintuna… we all know why!

Declaração de Honra

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Declaro, por minha honra, que o presente trabalho académico é original e foi elaborado por mim próprio (a), não se tendo recorrido a quaisquer outras fontes, para além das indicadas, usadas, adotadas literalmente ou adaptados a partir dos seus originais (em fontes impressas, não impressas ou na internet) e encontram-se adequados, identificados e citados, com observância das convenções do trabalho académico em vigor.

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RESUMO

A revolução tecnológica deixou de ser uma iminência para se converter em realidade. A tecnologia consolidou, sobre as sociedades, a emergência da mudança célere, no âmbito das qualificações da população e, consequentemente, da economia.

Na generalidade, a acessibilidade à informação dilatou as necessidades e exigências formativas. Particularmente, sobre o ensino e população estudantil, a universalização informática imprimiu, irreversivelmente, a pressão adequada para os benefícios da transformação digital e esta, por sua vez, é directamente dependente das valências da sua população. Os reais benefícios da transformação tecnológica apenas poderão fazer-se sentir sobre uma população, a médio e longo prazo, ao colocar estas plataformas no esquema integrado do Ensino.

A introdução da Realidade Virtual e da Tecnologia Háptica acresceram novas dimensões à educação e à forma como se abordam os desafios profissionais diários. Se, por um lado, é legítimo afirmar que a necessidade cria a tecnologia, por outro lado, não deixa de ser igualmente válido inferir que a tecnologia imprime uma irreversível necessidade de reavaliar as metodologias convencionais existentes, com sentido objectivamente crítico e construtivo. Quando aplicada ao ensino, esta estratégia tende a provocar alterações qualitativas e quantitativas sobre a pedagogia com o intuito de melhorar o aluno. No ensino em Saúde, a sua aplicação mudou o paradigma da abordagem ao doente e à doença. Pretende-se, inequivocamente, que um processo formativo mais aproximado do real e com maior número de repetições de simulação prévias ao acto médico, permita reduzir o número de complicações decorrentes do próprio, maior previsibilidade e menor morbilidade.

O ensino pré e pós-graduado em Medicina Dentária necessitam de uma ruptura evolutiva; de um salto qualitativo, em consonância com as reais potencialidades tecnológicas de que dispomos presentemente. Pretendem-se resultados mais previsíveis, atingidos por alunos com mais horas de treino e com a constância que a repetição imprime sobre a competência. Esta é uma real necessidade e oportunidade do Ensino.

Na formação em Medicina Dentária, as transições do ensino pré-clínico pré e pós-graduados para a realidade clínica constituem momentos de importância fulcral para o estudante. É na fase pré-clínica que este inicia o desenvolvimento da destreza manual que lhe permitirá desenvolver os finos e delicados movimentos manuais e percepção táctil necessários para a execução dos protocolos inerentes ao tratamento, em tecidos tão delicados como os tecidos orais. É, igualmente, nesta fase, que o aluno se encontra mais exposto à apreensão dos critérios de rigor e avaliação da execução de tais procedimentos. Tradicionalmente, o ensino pré-clínico ocorre por simulação em modelos sintéticos e/ou humanos ou não humanos não vivos, isentos da motivação e expectativas do paciente, dor e situações de urgência que envolvem os tratamentos de pacientes reais. A clareza de comunicação dos referidos critérios de avaliação permitirá, ao aluno, apreender e definir critérios próprios de execução, o que se coaduna com o objectivo maior de melhorar a simulação para atenuar a transição para a vida clínica, desta forma reduzindo tanto iatrogenia como a ansiedade associada à referida transição.

O ensino em Medicina Dentária no geral e, particularmente, em Dentisteria Operatória e Implantologia, dada a irreversibilidade consequente dos protocolos clínicos que lhes são subjacentes apresentam, no contexto prático do treino, um vector fundamental na aquisição de competências.

O objectivo desta investigação consiste na ampliação do ensino em Dentisteria Operatória e Implantologia Dentária através da criação de um simulador com Realidade Virtual e Tecnologia Háptica, centrada no auto-avaliação do estudante pela exposição do próprio a cenários virtuais simulados com tecnologia háptica. Estando identificadas as limitações inerentes não apenas ao ensino convencional, mas também aos simuladores disponíveis, nos campos específicos de Implantologia Dentária e Dentisteria Operatória, foi criado de um simulador com recurso em Realidade virtual e Tecnologia Háptica, imersivo e multimodal, baseado na auto-percepção educativa e pedagógica do estudante, permitindo a transposição das limitações primeiramente identificadas. A ausência de sistemas de avaliação universal, bem como a permanência da simulação com modelos artificiais e com escassa realidade patológica distanciam, ainda, a simulação convencional da realidade clínica. O projecto pretende a validação da utilização da Tecnologia Háptica e Realidade Virtual como métodos de melhoria do ensino em âmbito da Dentisteria Operatória e da Implantologia Dentária, com demonstrada aplicabilidade em cenários pré-clínicos.

A construção de um simulador jamais poderia ser feita sem uma estratégia colaborativa entre pedagogia e programação, sendo que o aporte da sensibilidade educativa em Medicina Dentária seria, primeiramente, introduzido com testes de um protótipo do simulador por profissionais experientes e docentes em Medicina Dentária do Instituto Universitário Egas Moniz (IUEM), Egas Moniz School of Health and Science, nas áreas da Implantologia Dentária e Dentisteria Operatória, no contexto de trabalho colaborativo e co-design do simulador. Ficou definido que os testes com estudantes apenas decorriam após 1) validação dos protótipos através testes com profissionais e sua publicação e 2) a introdução das alterações sugeridas pelos testes com profissionais numa versão mais definitiva e elaborada dos protótipos previamente aos testes com estudantes.

O desenvolvimento do simulador foi, portanto, subdividido em dois vectores correspondentes às áreas propostas: Implantologia Dentária (IMMPLANT) e Dentisteria Operatória (DENTIFY OD).

O IMMPLANT consiste numa sonda tecnológica que combina óculos de Realidade Virtual, um aparelho detector de movimentos colocado na região em frente à aparatologia de Realidade Virtual e um smartphone, conectados a um computador. A interacção do utilizador com o cenário virtual baseia-se numa manipulação bimanual na qual a mão livre (dominante) manipula a totalidade de 5 ou 6 graus de liberdade de uma mandíbula virtual ou de um implante dentário virtual, respectivamente, enquanto a outra mão (não dominante) opera um smartphone para manipulação mais refinada.

Por seu turno, o DENTIFY DO consiste numa simulação multimodal com tecnologia háptica e RV. O estudante/utilizador é colocado num ambiente virtual imersivo composto por estímulos visuais, auditivos e hápticos. Combina uma caneta háptica, óculos de RV e saída de áudio com sons de turbina dentária e de preparação cavitária, modelos dentários virtuais isolados ou inseridos numa arcada dentária. Para promover o realismo do ambiente virtual imersivo, a pega da caneta háptica foi substituída por um modelo 3D de uma turbina dentária com acoplamento adequado. Pretende-se que o DENTIFY DO seja uma ferramenta pedagógica para o ensino e treino da fase de preparação cavitária em Dentisteria Operatória, para alunos na fase de treino pré-clínico e com o objectivo de melhorar a destreza manual e manipulação tridimensional espacial, aumentar o número de repetições por sessão de treino e, adicionalmente, fornecer um conjunto de métricas correspondentes a cada sessão de treino, por utilizador. As métricas referidas permitem compilar dados relativos à progressão individual do utilizador e o conhecimento destes resultados tem como objectivo incutir, no aluno/utilizador, as capacidades de auto-crítica e auto-avaliação, bem como a tomada de percepção da sua curva de aprendizagem personalizada baseada em parâmetros objectivos e numericamente mensuráveis.

Os testes com utilizadores executados com profissionais de Medicina Dentária com os protótipos IMMPLANT e DENTIFY DO foram muito encorajadores ao progressivo desenvolvimento do DENTIFY. Os testes preliminares do IMMPLANT com profissionais envolveram entrevistas guiadas, questionários de usabilidade e de esforço mental e físico (workload), cujos resultados permitiram concluir que este constitui uma ferramenta de realidade virtual versátil e adequada para a educação em Implantologia Dentária. A estratégia de co-design supramencionada foi estendida ao DENTIFY DO, com recurso a questionários esforço mental e físico (workload), "cybersickness", usabilidade do sistema e entrevista guiada. Os resultados sobre a aceitação dos utilizadores permitiram concluir que se o DENTIFY DO apresenta potencial em melhorar o ensino desta disciplina, promove auto-avaliação e uma real imersão multimodal. Apresentou, portanto, potencial pedagógico em Dentisteria Operatória.

Por uma questão de estratégia evolutiva do simulador em Implantologia Dentária, foi uma opção consciente não executar, por ora, os testes com estudantes nesta fase, dado que, em reuniões de desenvolvimento do mesmo, se concluiu que era mandatório explorar suplementares potencialidades pedagógicas do mesmo, sob pena de se incorrer em subaproveitamento desta ferramenta.

No que concerne ao DENTIFY DO, foram realizados testes com estudantes num renovado simulador que incluiu, na sua reprogramação, os resultados obtidos com os testes prévios, conduzindo a alterações de software no que concerne à estética, manipulação e usabilidade do mesmo. Os testes com estudantes do 3º ano do Mestrado Integrado em Medicina Dentária do IUEM realizaram-se em diferentes sessões, tendo sido centrados na medição da autoavaliação e usabilidade pelos utilizadores (pré-graduados). Novamente, os resultados podem ser considerados como muito positivos. Os alunos aderiram muito positivamente às sessões com o simulador, apresentando métricas de performance indistintas entre utilizadores com e sem experiência prévia com Realidade Virtual, bem como resultados semelhantes entre gamers e não gamers. A possibilidade de avaliação momentânea e, desta forma, auxílio na criação de padrões de exigência críticos de performance, foram considerados como fundamentais na pedagogia veiculada pelo DENTIFY OD.

As potencialidades permitidas pela Realidade Virtual e Tecnologia Háptica permitem sugerir que devem ser incluídas na realidade pedagógica do ensino pré-clínico em Medicina Dentária, de forma definitiva, gradual e consistente apresentando métricas mensuráveis de performance que traduzam, numericamente e sem subjectividade, a curva evolutiva do estudante.

Este trabalho insere-se nos seguintes Objectivos de Desenvolvimento Sustentável da UNESCO:

ODS 4 - Garantir o acesso à educação inclusiva, de qualidade e equitativa, e promover oportunidades de aprendizagem ao longo da vida para todos – ao universalizar e permitir o ensino pela redução de custo da tecnologia e, portanto, pela sua acessibilidade.

ODS 9 - promover e fomentar a inovação – através da introdução das tecnologia háptica e realidade virtual no Ensino em Medicina Dentária. Promover melhor saúde oral para a comunidade em geral ao melhorar o ensino em Medicina Dentária.

Palavras-Chave: Medicina Dentária, Ensino, Realidade Virtual, Tecnologia Háptica, Simulador, DENTIFY, Dentisteria Operatória, Implantologia Dentária.

ABSTRACT

The technological revolution is no longer imminent, but, instead, a reality. Technology has consolidated, in societies, the emergence of rapid change in the qualifications of the population and, consequently, the economy.

In general, accessibility to information has expanded educational needs and demands. Particularly on the teaching and student population, the universalization of information technology has irreversibly imposed the appropriate pressure for the benefits of digital transformation and this, in turn, is directly dependent on the skill-set of its population. The real benefits of technological transformation can only be felt by a population, in the medium and long term, by placing these platforms in the integrated scheme of Education.

The introduction of Virtual Reality (VR) and Haptic Technology (HT) have added new dimensions to education and the way we approach daily professional challenges. If, on the one hand, it is legitimate to say that necessity creates technology, on the other hand, it is equally valid to infer that technology imprints an irreversible need to reevaluate preexisting conventional methodologies, with an objectively critical and constructive sense. When applied to teaching, this strategy tends to provoke qualitative and quantitative changes on pedagogy with the purpose of improving the student. In Health teaching, its application has changed the approach paradigm to both the patient and the disease. It is unequivocally intended for a training process that is closer to the real thing and allows for a greater number of simulation repetitions prior to the medical act, to reduce the number of complications resulting from the act itself, enable greater predictability, and lower morbidity.

Pre- and post-graduate education in Dentistry require an evolutionary break; a qualitative leap in line with the real technological potential that we currently have. More predictable results are desired from students with more training hours and with the constancy of competence that arises from repetition. This presents a real need and opportunity in Teaching.

In dental training, the transition from preclinical pre- and post-graduate teaching to clinical teaching are moments of central importance for the student. It is in the preclinical stage that the student begins to develop the manual dexterity that will

allow him/her to perform the fine and delicate movements and tactile perception necessary for the execution of the protocols inherent to treatment in such delicate tissues as oral tissues. It is also at this stage that the student is most likely to acquire the criteria of rigour and evaluation for the execution of such procedures. Traditionally, pre-clinical teaching occurs through simulation in synthetic and/or human or non-human non-living models, not considering patient motivation, expectations, pain and emergency situations that involve the treatments of real patients. Clear communication of the aforementioned evaluation criteria will allow the student to learn and define his own execution criteria, which is in line with the overarching goal of improving simulation to ease the transition to clinical life, thus reducing the anxiety associated with this transition as well as reducing iatrogenesis.

Given the irreversibility of clinical protocols in Dentistry in general, and particularly in Operative Dentistry and Implantology, teaching in these areas presents, in the practical side of training, a fundamental vector in skill acquisition.

The purpose of this research is to amplify Operative Dentistry and Dental Implantology teaching through the creation of a simulator with VR and haptic technology, centered on the student's self-assessment by exposing him/herself to simulated scenarios with virtual reality and haptic technology. Having identified the limitations inherent not only to conventional teaching in Implant Dentistry and Operative Dentistry, but also to available simulators, an immersive and multimodal simulator using virtual reality and haptic technology was developed, based on the student’s educational and pedagogical self-perception, allowing the transposition of the aforementioned limitations. The absence of universal evaluation systems, along with consistent simulation on artificial models with little pathological reality, distances conventional simulation from clinical reality. The project aims to validate the use of haptic technologies and virtual reality as methods to improve teaching in Dentistry and Implantology, with proven applicability in preclinical scenarios.

The simulator could never be built without a collaborative strategy between pedagogy and programming. The contribution of educational sensitivity in Dentistry would first be introduced by testing the simulator prototype with experienced Dentistry professionals and professors at the Instituto Universitário

Egas Moniz (IUEM), Egas Moniz School of Health and Science, in the areas of Dental Implantology and Operative Dentistry, in the context of collaborative work and co-design of the simulator. It was determined that tests with students would only take place after 1) validation of the prototypes through tests with professionals and their publication; and 2) the introduction of changes suggested by the tests with professionals in a more definitive and elaborated version of the prototypes prior to testing with students.

The development of the simulator was therefore subdivided into 2 vectors corresponding to the proposed areas: Dental Implantology (IMMPLANT) and Operative Dentistry (DENTIFY OD).

IMMPLANT consists of a tech probe that combines a VR head-mounted display, a small hand tracking device placed in the front side of the VR headset and a smartphone, all connected to a laptop. User interaction with the virtual scenarios follows a bi-manual approach where the free (dominant) hand directly manipulates all 6 or 5 degrees-of-freedom of either the mandible or implant, respectively, while the other (non-dominant) hand operates a smartphone for more fine-tuned manipulation.

DENTIFY OD is a multimodal simulator that resorts to VR and haptic pen technology. It places the student/user in an immersive virtual environment, composed of visual, auditory and haptic stimuli. It combines a haptic pen, VR goggles with audio output, turbine and drilling sounds, virtual dental models of isolated teeth and complete dental arches. To promote realism of the virtual environment immersion, the haptic pen grip has been replaced by a printed model of a dental turbine. It is intended to be a pedagogical tool for training and teaching the cavity preparation phase in OD, aimed at students in preclinical training for the purposes of improving the student's manual dexterity and three-dimensional spatial manipulation, increasing the number of repetitions per training session, and, additionally, providing a set of metrics corresponding to each use, per user. The simulator also allows for users to save their data per user and per simulation, thus allowing the user to compile a graphical progressive evaluation. Exposing the student to DENTIFY's metrics results aims to stimulate self-assessment and self-criticism, as well as the perception of the user's own learning curve on the grounds of objective and numerically measurable parameters.

The tests performed by dental professionals with the IMMPLANT and DENTIFY OD prototypes were very encouraging to the progressive development of DENTIFY. Preliminary tests of IMMPLANT with professionals involved guided interviews, as well as usability and workload questionnaires, whose results allowed us to conclude that it constitutes a versatile virtual reality tool suitable for education in Dental Implantology. The co-design strategy mentioned above was extended to DENTIFY OD, using questionnaires on workload; cybersickness; system usability; and guided interviews. The user acceptance results allowed for the conclusion that DENTIFY OD shows potential in improving its teaching, promotes self-assessment, and provides a real multimodal immersion. It showed pedagogical potential in Operative Dentistry.

Regarding of the Dental Implantology’s evolution, it was a conscious choice to not run the tests with students at this stage since, in development meetings, it was concluded that it was mandatory to explore more of its pedagogical potential, lest this tool be underutilized.

Regarding DENTIFY OD, tests were performed with students on a renewed simulator, which included, in its reprogramming, results obtained from the previous tests, leading to software changes regarding its aesthetics, handling and usability. Tests with 3rd year Dental Medicine Integrated Master students at the IUEM took place in different sessions and focused on measuring self-assessment and usability by the users (undergraduates). Again, the results can be considered very positive. Students adhered very positively to sessions with the simulator, presenting indistinct performance metrics between users with and without previous experience with Virtual Reality, as well as similar results between gamers and non-gamers. The possibility of instant evaluation and, thus, helping in creating self-criticism in performance standards were considered fundamental in DENTIFY OD’s pedagogical attributes.

The inherent potential of Virtual Reality and Haptic Technology suggests that these should be included in the pedagogical reality of pre-clinical teaching in Dentistry, in a definitive, gradual, and consistent manner while presenting measurable performance metrics that reflect the student’s evolutionary curve, numerically and without subjectivity.

This work is in conformity with the following UNESCO Objectives for Sustainable Development:

ODS 4 – Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all – by universalizing and allowing teaching by cost reduction of the available technology and, therefore, allowing accessibility.

ODS 9 – to promote and foster innovation – by further enabling haptic technology and virtual reality in teaching Dental Medicine. To promote better oral health care services to the general community by improving dental teaching.

Keywords: Dental Medicine, Teaching, Virtual Reality, Haptic Technology, Simulator, DENTIFY, Operative Dentistry, Dental Implantology.

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ABBREVIATIONS LIST

RV - Realidade Virtual

HT – Haptic Technology

HVRS – Haptic Virtual Reality Simulation

VR – Virtual Reality

VRDTS – Virtual Reality Dental Training Systems

DENTIFY OD – DENTIFY Operative Dentistry

CHAPTER 1

CONTRIBUTOR ROLES TAXONOMY (CRediT)

Identification and recognition of individual contributions from the authors of the articles presented in this PhD Thesis proposal:

Chapter 2 – An immersive educational tool for dental implant placement: A study on user acceptance

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METHODOLOGY	Ezequiel Roberto Zorzal Soraia Figueiredo Paulo Pedro Rodrigues José João Mendes Daniel Simões Lopes
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VALIDATION	Daniel Simões Lopes
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FUNDING ACQUISITION	Daniel Simões Lopes

Chapter 3 – Usability, acceptance, and educational usefulness study of a new haptic operative dentistry virtual reality simulator

TERM	**DEFINITION**
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Chapter 4 – Preclinical dental students self-assessment of an improved operativre dentistry virtual reality simulator with haptic feedback

TERM	**DEFINITION**
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CHAPTER 2

GENERAL INTRODUCTION

Preclinical teaching in Dentistry involves two phases (1): theoretical schematic representation of procedures to be performed and their replication in models so that, in a second phase, they can be applied in real clinical situations, both under supervision.

Initially, procedures were simulated on real exodontically removed teeth (2). In 1894, Fantomas were introduced and the repetition of procedures on these models has been the cornerstone of simulation in Dental Medicine (3).

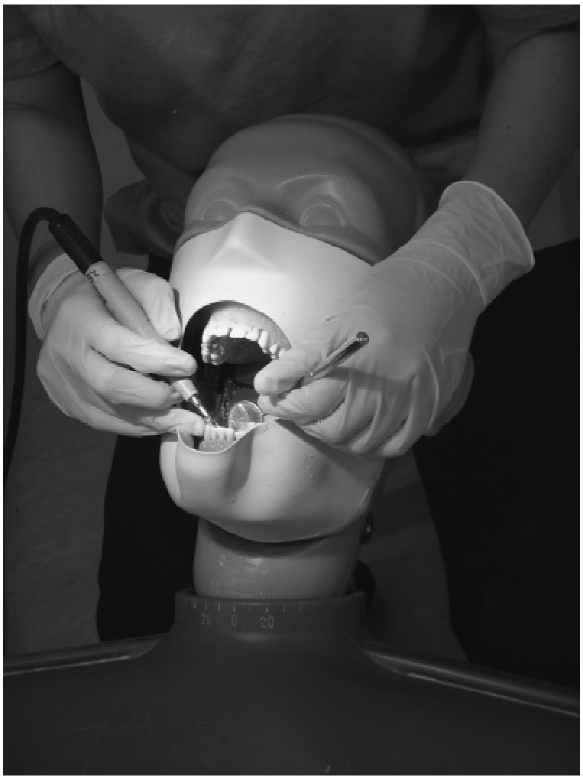

Figure 1 - A modern phantom head simulator (2)

The preclinical pedagogical use of phantom heads including oral cavity models allows the improvement of protocol skills of clinical acts prior to treatment of real patients (4). Its use is ergonomically correct; allows for proper handling of the rotating instrument and mirror; allows for a support finger to maintain stability during handling; and allows for the recreation of theoretical clinical conditions after verbal and visual instructions on how to perform them (3). The limitations to the use of phantom heads are the absence of real clinical situations; the insufficiency of pathological models; and the absence of universal criteria of evaluation, which in turn underlie the subjective monitoring of each evaluator (5). The amount of time required for constant supervision of each student's procedure may cause inherent difficulties in the student/mentor ratio (6). Clinical teaching with limited resources may cause anxiety in some less experienced students (7). Additionally, the effectiveness of practice sessions with phantom heads and other plastic models depends on the tutor's own assessment skills, reflected in his ability to produce feedback to evaluate the student's constant progress (8). Self-assessment plays an important role in identifying learning needs, understanding decision-making criteria and task performance patterns, and the learning process can be enhanced by self-perception of learning (9).

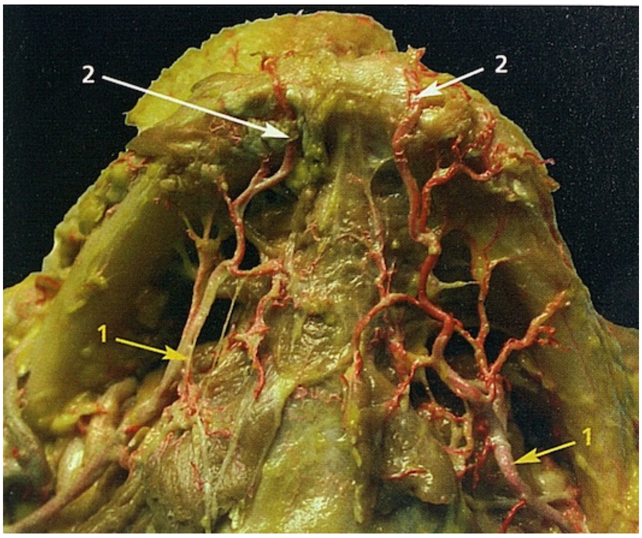

Figure 2 - Submental Arteries and trans-milohyoyd branches (10)

Simulation in animals and cadavers, with manipulation of real tissues (animal or human) persists in training. The use of human cadaveric material persists as the gold standard in medical training.

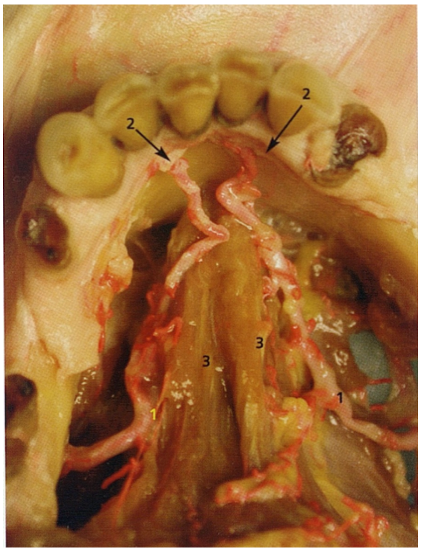

Figure 3 - Perforating Branch of Sublingual Artery that substitutes Submental Artery; 2) Near incisiors; 3) Geniohyoid Muscle. branches (10)

However, anatomy differs from animals to humans. The use of human cadavers has been subject to ethical and legal issues, resulting in the increasing unavailability of this material for teaching (11). The scarcity of donated human material for teaching and research, tissue degradation, high economic costs of storage and logistics associated with the simulation's lack of repeatability, have led to limitations in its use for teaching (11).

The aforementioned limitations regarding traditional teaching, in association with the opportunities offered by current technology, created the need and opportunity for its introduction in the context of pre-clinical training in Dentistry.

The most universally accepted example of VR application in training is aviation, in which there are universal and mandatory evaluation criteria for pilot training, as well as mandatory periodic evaluation of experienced pilots (6). VR refers to technology that codes and compiles computer generated multisensory data to be perceived by users as alternative realities, allowing them to immersively interact with simulated tasks, events or scenarios frequently using head mounted displays.

Figure 4 - VR Headset Oculus Quest 2™ (12)

Haptic technology is defined as the science of applying tactile sensation (touch) and control to interact with computerized applications (13). Compared to aviation, the use of VR and haptics in Dentistry is in its infancy (6).

Figure 5 - 3D Systems Touch Haptic Device® (14)

The concept of Virtual Reality Dental Training Systems (VRDTS) was introduced by Ranta et al in the 1990s (15). The introduction of VR simulators in dental education has been widely studied pertaining to the pedagogical potential these may instill in students. There are several commercially available simulators on the market, such as PerioSim (16–18); Haptic Technology Enhanced Learning (HapTEL) (19); the Virtual Dental Patient (20,21); VirDenT (22–25); iDental system (26–28); Forsslund Systems (29,30); Simodont (31,32); VOXEL-MAN (33–35), Virteasy Dental (36,37); the Individual Dental Education Assistant (IDEA) (38); the Virtual Education System for Dentistry (39); DentSim (40); Voxel-Man (35); among others.

In oral and maxillofacial surgery, studies report that students undergoing VR learning can learn motor skills faster, compared to students trained only in phantom heads (11). Corrêa et al studied a simulator for regional inferior alveolar nerve block. They found that the simulator was adequate in the following parameters: depth, anatomical location of the puncture, and resistance to progression offered by virtual tissue resistance (41). Jasinevicius et al showed that students without haptic training received about five times more training hours compared to students who were trained using VR (42). In Periodontology, there are simulators that allow you to use a virtual periodontal probe in the diagnostic phase for measuring periodontal pocket depth. In the treatment phase, virtual instruments appropriate to the anatomical region are selected for virtual subgingival tartar removal. In the evaluation phase, it can be tactilely checked whether the tartar has been completely removed (1). In Endodontics (43), users with prior haptic training were found to perform the access cavity faster. Their learning curves showed a reduction in execution time with only a few simulations. In Oral/Maxillofacial Surgery (44) and Implantology, VR associated with haptic technology allows to decrease the discrepancy between simulation and surgical protocol, on a virtual model obtained from the patient’s radiological data. The simulated surgical planning is transferable to surgery.

In a study at the University of Pennsylvania (45), students trained using haptics and VR demonstrated faster learning; reached the same level of performance; were able to perform more procedures per hour; and requested more assessments per procedure per hour than students trained in traditional labs. In a study at Tokyo Medical and Dental University (46), treatment completion times by 5th year students with haptic training were lower, and virtual simulators appeared to require less supervision time by faculty members.

In operative Dentistry, VR and haptic simulation can be a determining factor given its tactile complexity, particularly in the resistance that different elements (enamel, dentin, pulp, restorations and caries) with different degrees of mineralization and density offer to the progression of cutting instruments (47). Studies show better psychomotor performance in students submitted to HVRS (48,49).

Unlike plastic models, simulators with haptic technology are much more cost effective since no physical models need to be replaced. Additionally, since haptic devices measure the forces applied by the user when touching the virtual model, it is possible to detect whether the user is being too aggressive (16). Simulators with haptic technology also allow (50):

1. Improved usability by enabling multimodal immersion in regards to touch, sight and sound. HT adds realism to the user experience:
2. Establishing mechanical sensitivity by allowing the user, unequivocal and unmistakable tactile confirmation, and thus promoting a safer experience;
3. Cost effectiveness - provides a low-cost alternative when compared to costs associated with plastic models;
4. Self-Assessment - defined as the ability to allow immediate and instantaneous user feedback regarding tactile stimulation, without bias;
5. Ergonomically correct positioning;
6. Standardised evaluation for consistency and uniformity;
7. Faster acquisition of manual dexterity, tactile dexterity, and eye-hand coordination when compared to students who underwent only conventional instruction.

Despite the aforementioned advantages, some limitations have been pointed out regarding the use of simulators with VR and haptic technology in education. The disadvantages associated with these simulators can be classified into 2 major classes: Hardware and Software design limitations (51). Headset resolution is not high enough, which may change the colors of virtual tissues (less similar to real tissues), and their resolution is not high enough, which can also lead to unwanted effects such as dizziness and nausea (37). The altered resolution that comes with its use may not allow for the subtle distinction between virtual tissues, so a lower resolution may cause a lack of sharpness in the simulation (52). The absence of a physical point for resting a support finger may compromise the refined, short and precise movements required for treatments in the oral cavity without iatrogenic injury to adjacent healthy tissues (53). It is also noted that the absence of bimanual manipulation may compromise the realism of simulation immersion (54).

Regarding software limitations, the content of virtual scenarios may be insufficient by not allowing different exercises with different degrees of difficulty, thus limiting supervision of the student’s gradual progress (53). On the other hand, studies report that the simulation of the force applied on the haptic pen is not realistic enough (55), which prevents translating the realistic progression of virtual cutting instruments on bone types with different corticalization after tooth loss, as well as on the different degrees of mineralization of dental tissues (which confer different resistance to the progression of cutting instruments in the real clinical scenario). Currently, the sensation of force performed on a haptic simulator is the result of an algorithm, which differs from the contact of a rotary instrument with real tissue (56,57), although kinematic data and self-perception on haptic feedback contribute to enhance the acquisition of manual dexterity at earlier stages of preclinical training (58). In turn, the deformation presented by the simulators on virtual soft tissues should be improved since they do not translate factors such as elasticity and density (51). Some simulators do not provide results that allow for objective assessment, although the perception of the results is beneficial for the student's self-perception (51). There is therefore a need for self-assessment by the students, associated with the self-learning option (59).

Despite the aforementioned limitations, e.g., the absence of multiple scenarios, the absence of indirect vision, HVRS may contribute to improving preclinical pre- and postgraduate dental education. We proposed to overcome some of the limitations referenced in the literature, as described below in the papers published.

CHAPTER 3

AN IMMERSIVE EDUCATIONAL TOOL FOR DENTAL IMPLANT PLACEMENT: A STUDY ON USER ACCEPTANCE

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An immersive educational tool for dental implant placement: A study on user acceptance

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A R T I C L E I N F O

Keywords:
Implantology
Dental implant
Virtual reality
Bimanual interaction
Mobile device

A B S T R A C T

Background: Tools for training and education of dental students can improve their ability to perform technical procedures such as dental implant placement. Shortage of training can negatively affect dental implantologists' performance during intraoperative procedures, resulting in lack of surgical precision and, consequently, inadequate implant placement, which may lead to unsuccessful implant supported restorations or other complications.
Objective: We designed and developed IMMPLANT a virtual reality educational tool to assist implant placement learning, which allows users to freely manipulate 3D dental models (e.g., a simulated patient's mandible and implant) with their dominant hand while operating a touchscreen device to assist 3D manipulation.
Methods: The proposed virtual reality tool combines an immersive head-mounted display, a small hand tracking device and a smartphone that are all connected to a laptop. The operator's dominant hand is tracked to quickly and coarsely manipulate either the 3D dental model or the virtual implant, while the non-dominant hand holds a smartphone converted into a controller to assist button activation and a greater input precision for 3D implant positioning and inclination. We evaluated IMMPLANT's usability and acceptance during training sessions with 16 dental professionals.
Results: The conducted user acceptance study revealed that IMMPLANT constitutes a versatile, portable, and complementary tool to assist implant placement learning, as it promotes immersive visualization and spatial manipulation of 3D dental anatomy.
Conclusions: IMMPLANT is a promising virtual reality tool to assist student learning and 3D dental visualization for implant placement education. IMMPLANT may also be easily incorporated into training programs for dental students.

1. Introduction

Preoperative dental implant placement is essential to ensure successful oral surgery outcomes, which positively influences subsequent prosthetic stages. Due to the anatomical complexity of both the maxilla and mandible, as well as the risk of damaging existing vital structures (e.g., maxillary sinus, arteries, submandibular glands and nerves), precise 3D perception of these anatomical risks and their spatial relationships is of great importance in order to carry out proper alveolar bone diagnosis and, more importantly, to guarantee precise implant positioning and inclination [1,2].

Computed tomography (CT) is the standard imaging modality for dental diagnosis and oral implant procedures. From CT data, 3D views and volume rendering images of the mandible and maxilla are generated [3]. However, the available dental image workstations are composed of 2D screens, mouse and keyboard input devices, which users operate to interact with the digital content through Windows-Icons-Menus-Pointers (WIMP) interfaces. Such interfaces often fail to be effective in the execution of tasks related to 3D content visualization and manipulation [4].

Computer-aided implant placement tools allow users to position and rotate virtual implants using patient-specific CT data as image references [3]. Conventional WIMP systems enable implantologists to plan where should an implant be placed, as well as to visualize neighboring

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anatomical structures. Such tasks are hindered by WIMP interfaces. On one hand, WIMP interfaces are crowded with menus and icons. On the other hand, CT images and volume rendering images are displayed on flat media that do not offer a proper 3D perception of patient-specific anatomy.

Besides hampering 3D visual insight, performing virtual implant placement and inclination based on 2D images has the drawback of being an iterative process: when the user properly positions and/or inclines the implant in one anatomical plane, their is the risk of mispositioning or misaligning the implant on the remaining axes or angles. Therefore, planning implant placement may benefit from immersive technologies that combine Virtual Reality (VR) with handheld devices, as they promote more natural interfaces for 3D camera control and 3D perception. Moreover, according to [5], VR is an excellent medium for mentoring while the student/trainee carries out a series of precise movements.

Several studies have specifically explored new forms of interaction to improve implant planning by combining Augmented Reality (AR) or VR stereoscopic headsets, input controllers, and interactive surfaces [6–10, 4,11].

Regarding education, several undergraduate and postgraduate programs [12–14] do integrate VR technologies to support implantology dental courses [15], as VR scenarios do not carry clinical consequences as users perform procedures on virtual dental patients [16]. Moreover, VR scenarios allow countless repetitions, which is an essential feature for learning dental practices. VR also proves to be useful when it comes to training, as VR allows the simulation of the placement of dental implants regarding position, dimensions and proximity to vital structures [17], hence, stimulating the student's adaptive capacity and versatility by allowing alteration of implant placement, and avoiding anatomical accidents [17], in order to meet the treatment aesthetic and functional demands, as well as avoiding injury to anatomically important structures in the virtual environment.

In this paper, we present IMMPLANT (IMMersive Implant PLANning using a Mobile Touchscreen) an interactive VR educational tool for preoperative planning of dental implant placement. We explore the versatility of handheld device combined with hand tracking to improve object manipulation and visualization of 3D dental content i.e., subject-specific 3D mandible and virtual implant. Our goal is to verify if IMMPLANT can positively assist teaching and learning experiences for planning implant placement procedures, namely, if IMMPLANT can enhance 3D visualization and manipulation of anatomical content in implantology education. In order to evaluate the usefulness, usability, and user acceptance of IMMPLANT's interactive and immersion features, we conducted a user-study with professional dentists.

2. Materials and methods

2.1. Interactive system overview

IMMPLANT consists of a tech probe that combines a VR head-mounted display, a small hand tracking device placed in the front side of the VR headset and a smartphone, all connected to a laptop (Fig. 1). User interaction follows a bi-manual approach [18] where the free (dominant) hand directly manipulates all 6 or 5 degrees-of-freedom of either the mandible or implant, respectively, while the other (non-dominant) hand operates a smartphone for more fine-tuned manipulation.

2.2. 3D image data

A single dental Cone-Beam Computer Tomography (CBCT) dataset was used, provided by our clinical partners from Centro de Investigação Interdisciplinar Egas Moniz (Egas Moniz University Institute – Almada, Portugal). The acquired stack of 2D medical images was converted from DICOM (*.dcm) to bitmap (*.bmp) so that the image data could be imported into Unity environment. A patient-specific model of the mandible (Fig. 3(a)) was 3D reconstructed from the 2D cross-sectional CBCT images following an image-based geometric modeling pipeline relying on free and open-source tools [19,20].

2.3. Spatial user interface

The virtual scene consists of a minimalist black background (to avoid distractions) populated with the following 3D graphical elements: a floating 3D white mandible mesh, a virtual implant, a green cylinder attached to the implant placement site, the inferior alveolar nerve colored red, virtual hands and a virtual smartphone. During free hand manipulation the virtual smartphone interface presents a 1×1 layout displaying a *Free Manipulation* message (Fig. 2). Once the implant is attached, the virtual smartphone's interface splits in a 2×1 layout with the top and lower sections for selecting translation or inclination input modes, respectively. After selecting either mode, the user has access to directional pads to perform finer adjustments upon implant's position and inclination. To apply constrained manipulations, a translation or rotation widget with color coded guides (x – red, z – blue, y – green) appear attached to the implant's spatial reference system.

For precise implant placement and inclination, a set of directional arrows are made available on the smartphone's screen. The touchscreen is divided into top and bottom sections to support precision tasks for translation and rotation movements using thumbs (Fig. 2). Haptic feedback is provided to the user in the form of a smartphone vibration, confirming the implant was placed successfully.

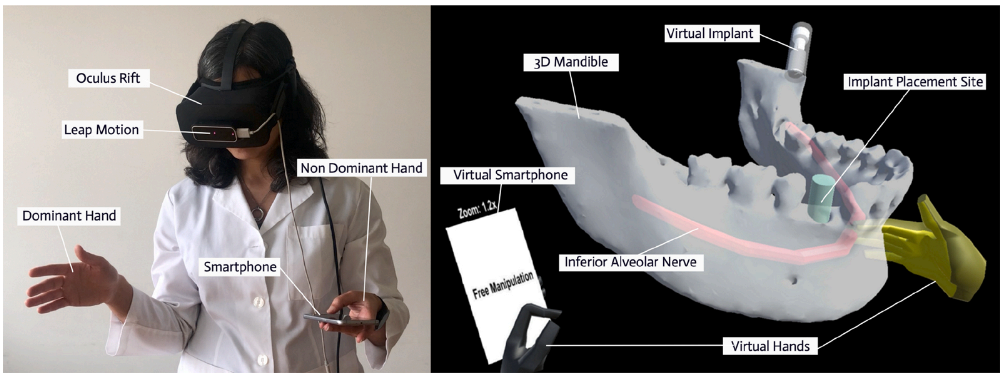

Fig. 1. User interacting with IMMPLANT, an immersive prototype that combines a VR headset, a small hand tracking device and a smartphone. Gross implant position and orientation are performed with the user's free (dominant) hand while finer adjustments are inputted via the smartphone's touchscreen. Once immersed, the user interacts with a patient-specific 3D model, a virtual implant and manipulation widgets (lower right corner).

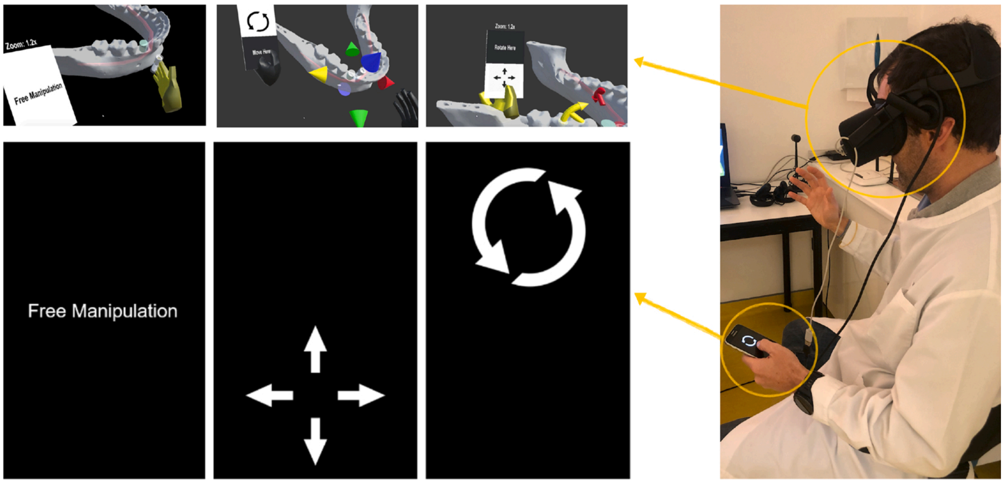

Fig. 2. Smartphone interface: free manipulation screen (left), translation screen (center), rotation screen (right).

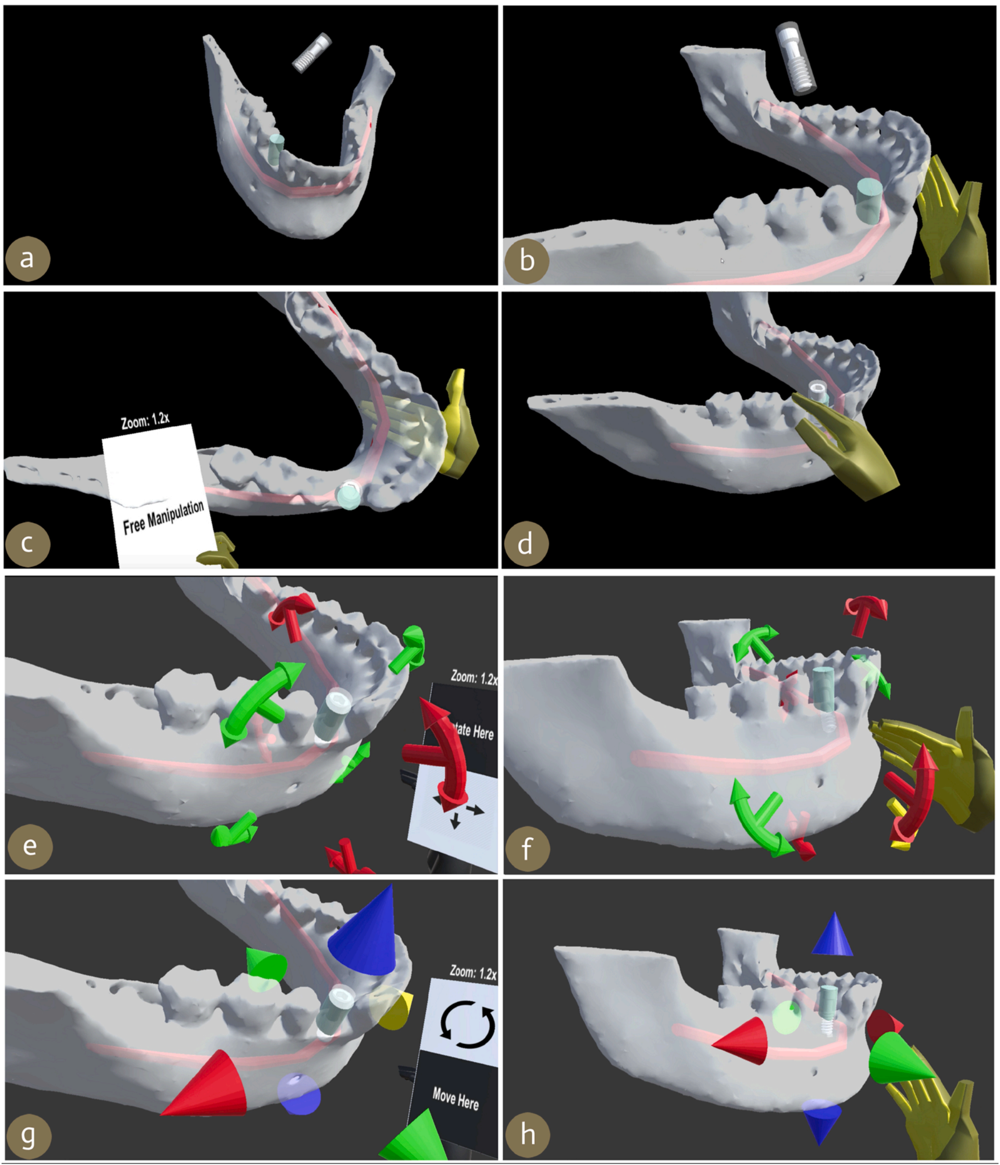

Fig. 3. Example of a sequence of IMMPLANT expedite, free hand interaction steps: (a) a 3D model of a mandible and a virtual implant are made available to the user and are placed "floating" in the 3D virtual scene; (b–d) users can directly manipulate (translate and rotate) either the 3D mandible or virtual implant using their (dominant) free hand controlling all 6 degrees-of-freedom; (e–h) users can apply more constrained manipulations in position and rotation by interacting with 3D rotation (e–f) and 3D translation (g–h) widgets that give access to 1 degree-of-freedom at a time.

Visual aids were added to promote precise adjustments of the implant with directional pads (Fig. 3(e–h)). For successful implant planning and to prevent further postoperative complications, it is crucial to visualize the spatial relations between anatomical structures and to be aware of relative distances between the implant and vital structures (e.g., inferior alveolar nerve and surrounding teeth). Therefore, visual feedback on implant collision with such structures is a necessary feature. To this end, the implant is embedded within a safety cylinder with a radius equal to the implant's radius plus 1.5 mm and a height of 2.0 mm. These values are normative and ensure safety distances from the inferior alveolar nerve and neighbouring teeth. If the implant collides with a vital structure, then the safety cylinder turns red.

2.4. Free hand and handheld device interaction

With their free (dominant) hand, users can directly manipulates all 6 degrees-of-freedom of either the mandible or implant. The 6 degrees-of-freedom of the users hand are mapped to the mandible or implant local reference system. Free manipulation is performed with an opened hand while pressing and holding their thumb on the touchscreen. Once the virtual hand collides with the 3D object the user wants to manipulate (i.e., mandible or virtual implant), the virtual hand turns yellow as a confirmation that the object is locked and the selected 3D object will start following the user's dominant hand movement (Fig. 3(b–d)) according to the hand's spatial reference, which is mapped directly to the object. To let go of the object, the user must lift the thumb of the smartphone's screen and move the hand away from the 3D object.

With their other (non-dominant) hand, users operate a smartphone for activating different selection modes and to apply more fine-tuned manipulations. More specifically, through the smartphone's touchscreen, users can define manipulation modes (free and constrained manipulation), selection modes (i.e., select between mandible or implant and select single translation axis or single rotation axis rotation). To apply minute translations or rotations to the virtual implant, user's select with their free hand one of the color coded widgets axes and, through the touchscreen, input minute translations or rotations to the virtual implant in relation to the virtual mandible.

Note that the virtual implant just has 5 degrees-of-freedom (3 translations and 2 rotational axes to define its inclination) as the rotation along the implant's longitudinal axis was discarded as the implant is a helically symmetric object.

2.5. Apparatus

Our setup resorted on a laptop computer (Asus ROG G752VS, Intel Core i7-6820HK Processor, 64 GB RAM, NVIDIA GeForce GTX1070) running Windows 10, along with a smartphone (Samsung Galaxy S7 32 GB RAM) running Android 9.0 Pie, an Oculus Rift and a Leap Motion controller mounted onto the frontal panel of the VR headset (Fig. 4). In addition, we used a router (Router TP-Link model TL-WR841N) to enable communications between the smartphone and laptop. Code development was performed using Unity 2017.2.0f3 and C# scripting.

Fig. 4. Equipment set for running IMMPLANT.

2.6. Participants

A total of 16 participants (12 male, 4 female) with ages ranging from 23 to 64 (Median = 32, SD = 10.23) were invited for our assessment study. All participants were medical dentists, 4 specializing in oral rehabilitation, 2 in prosthodontics, 1 in implantology, 1 in endodontics, 1 in periodontics, 3 in oral surgery, and 4 in general dentistry, ranging from 1 to 20 years of experience. All participants referred that they were right-handed. Every participant dealt with touch screens on a daily basis and 8 participants never dealt with virtual or augmented reality applications. Implantologists and Oral Surgeons frequently use 3D visualization software for dental implant placement, while the remaining participants do not use this type of software. Fig. 5 shows the alluvial diagram that highlights important user characteristics emphasized by color and node clustering.

2.7. Tasks

Participants were asked to place a virtual implant at a specific bone-loss area location within a subject-specific 3D model of a lower jaw (Fig. 7). In particular, participants were requested to perform the implant placement tasks by, firstly, placing the implant as close as possible to the predetermined location and, secondly, by adjusting the position and inclination with finer input through thumb gestures (Fig. 6). Participant feedback regarding IMMPLANT's limitations and benefits, as well as the adequacy of IMMPLANT to support implant placement, was then gathered via questionnaires and guided interviews, Furthermore, we aim to include a System Usability Scale (SUS) [21] questionnaire for the purpose of measuring usability, and a NASA Task Load Index (NASA-TLX) [22] questionnaire for perceived workload rates to assess prototype effectiveness. Each task could take at most 20 min, after which the task was interrupted.

2.8. Procedure

All tests were conducted in an office at the Centro de Investigação Interdisciplinar Egas Moniz's Clinic. The expected duration of a test session was about 20–30 min and was divided in six phases: (i) informed consent and demographics, (ii) introduction, (iii) free experimentation, (iv) task execution, (v) questionnaires, and (vi) guided interview. At the beginning of each session, we asked participants to sit through the test session and to fill in an informed consent form agreeing to the study conditions and terms, followed by a demographic questionnaire. Afterwards, participants were given a short demonstration of IMMPLANT's interface and interaction features. Then, users were prompted to freely explore the interface while performing a habituation task for up to 5 min. This phase was followed by task execution were we asked participants to complete implant placement tasks. This phase was followed by participants filling in preference and satisfaction questionnaires regarding the interface and the tasks undertaken. Finally, a guided interview was conducted to capture the participants' impressions about the interface and interaction techniques, as well as their potential application in dental implant placement, both in surgery and dental implant education (through preoperative simulation). Participants were invited to elaborate as much as possible on the issues they found to be the most relevant from their experience. We also requested their thoughts and opinions regarding improvements to the system. In addition to questionnaire answers and interview transcripts, data gathered also included observational notes taken during test sessions.

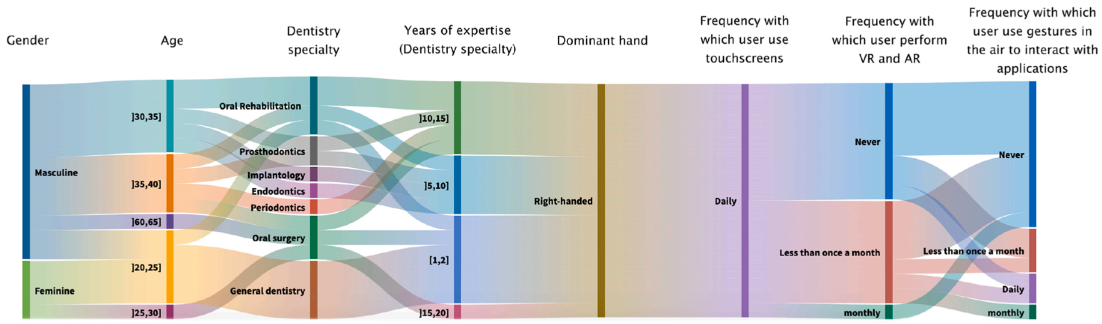

Fig. 5. Alluvial diagram summarizing the demographic data from profiles included in the assessment study. In this diagram, demographic data is categorized in each column and the ratios of the categories are presented. Colored edges between columns indicate direct relations between demographic attributes. The sizes of edges and flows are therefore linked to the values containing the same couple of nodes.

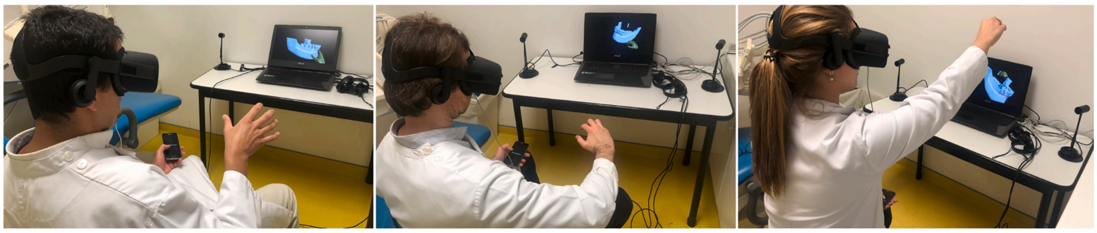

Fig. 6. Participants during an assessment evaluation session.

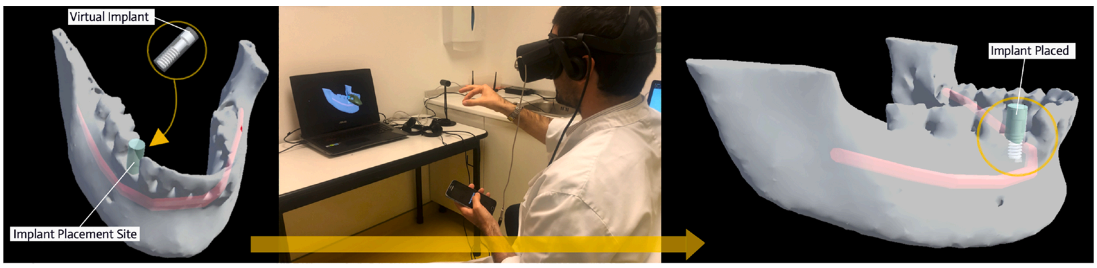

Fig. 7. Participants were asked to place a virtual implant at a specific bone-loss area location within a subject-specific 3D model of a lower jaw.

3. Results and discussion

During all the task performances, users revealed an interesting pattern: they all started by freely manipulating the mandible to visually explore the 3D nature of its anatomy, to then orient and place it in an appropriate point of view; afterwards user's freely manipulated the virtual implant placing it near the target site, to then perform finer translation and inclination adjustments via touchscreen. Whenever they were not satisfied with the result, user's would remove the implant and try another placement and inclination in free manipulation mode followed by constrained adjustments.

Regarding user and satisfaction questionnaires, results indicate that our VR system is easy to use and promotes greater spatial awareness of the 3D dental model. As for the results from usability tests they reveal that participants considered the system easy to learn. However, while participants were relatively quick to identify the structures of interest (bone-loss, bone height, bone width and nerve position) via 3D camera control, they acknowledged some difficulty selecting the predetermined implant position and inclination, thus adding to the time necessary to complete the task. Furthermore, participants in our evaluation suggested that the user experience and interaction methods were adequate. Despite the lack of familiarity with VR, results are highly encouraging as most professionals considered that IMMPLANT complements conventional WIMP interfaces since it provides greater camera control for 3D anatomical visualization. All senior participants mentioned the possibility of adopting IMMPLANT as a surgical training and/or medical educational tool in everyday practice.

In addition, we evaluated participants perception of usability through a SUS questionnaire with a usability score of 83.91, revealing that IMMPLANT has good usability and high learnability (Table 2). We also studied the subjective workload experienced by users during the prototype evaluation. For this purpose, we conducted a workload analysis study using NASA-TLX. Fig. 8 shows the subscale summary of workload analysis. Thus, NASA-TLX provides support for the proposed system designs as being effective solutions for reducing the ergonomics gaps in terms of mental workload and, to a lesser extent, the physical workload, imposed by the system [23]. The findings suggest that this approach shows a low rating for the entire workload-dimension. The results regarding the workload are similar in general terms, implying that this systematic task process with IMMPLANT was not considered difficult.

Moreover, users felt confident using the system, which provided the medical dentists a feeling of control, in fact, participant 4 stated "the system complements conventional practice because it allows for several repetitions, as well as recurring practice", while participant 6 stated "[IMMPLANT] allows a better orientation in the placement of implants when compared to traditional implant planning software" and participant 8 mentioned "the biggest benefit of this VR system is its

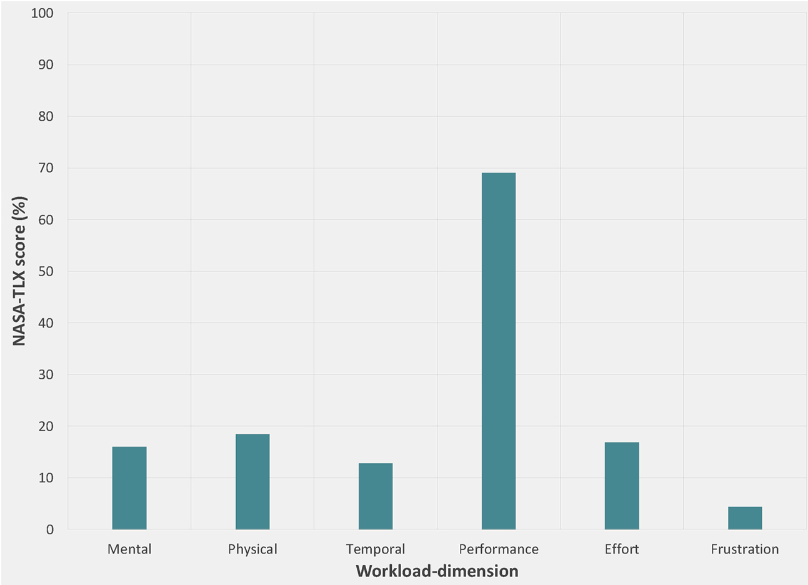

Fig. 8. NASA-TLX workload analysis results.

interactivity and ease to visualize anatomical structures". Table 1 shows the participants' feedback to the prototype's features, revealing all were well received.

Despite the positive results, our study has several limitations. For instance, wearing a VR headset can force the wearers to modify their posture and potentially affect their performance when attempting to manipulate a 3D object with their bare hand [24]. Other metrics such as fatigue, stress tests and cognitive load are important variables to understand the limitations of the proposed tool, yet they were not considered in this paper. The greatest limitation of our study consist in the lack of a comparative study between IMMPLANT and standard implant software that could include a quantitative analysis of user performance, with dozens of dental medicine students as participants, that would not only assess but validate IMMPLANT as a user-friendly VR tool for learning implant placement. Despite these limitations, while our study is exploratory, we see it as the precursor to a new generation of user-friendly educational tools for planning implant placement. Finally, the application of immersive VR education tools in both undergraduate and postgraduate dentistry programs, although allowing for immediate evaluation and instantaneous feedback, is far from being universal and

Table 1
Results from the user preferences questionnaires (median, (interquartile range – IQR)).

Features	Statement	Median (IQR)
General impressions	The anatomy is realistic.	5 (2)
	It is useful to be able to see the internal anatomy (anatomical structures potentially damaged by implant osteotomy).	5.5 (1)
	It is useful to see the depth of implant insertion.	6 (1)
	Colors and graphic elements represented the location of the implant osteotomy and insertion.	5.5 (1)
	It is easy to use.	5 (2)
	It is fast learning.	5 (2)
	It is useful for teaching implant insertion.	5.5 (1)
	Interactivity promotes focus and learning.	6 (0)
In comparison with conventional teaching for implant placement	It allowed you to identify anatomical landmarks more easily.	6 (1)
	It is easier to use.	5 (1.25)
	It is faster to learn.	5 (2)
	It is useful for teaching.	6 (0)
	It is easier to memorize the correct implant placement.	6 (1)

Table 2
Descriptive statistics of the SUS questionnaire: average, median, minimum value – Min, largest value – Max, standard deviation – SD, interquartile range – IQR.

SUS item	Average	Median	Min	Max	SD	IQR
I think that I would like to use this system.	4.50	5.00	3.00	5.00	0.73	1.00
I found the system unnecessarily complex.	1.38	1.00	1.00	3.00	0.62	1.00
I thought the system was easy to use.	4.44	4.50	3.00	5.00	0.63	1.00
I think I would need technical support to be able to use this system.	2.19	2.00	1.00	4.00	1.17	2.00
I found the various functions in the system were well integrated.	4.19	4.00	3.00	5.00	0.75	1.00
I thought there was too much inconsistency in this system.	2.06	2.00	1.00	4.00	1.12	1.25
I would imagine that most users would learn to use this system very quickly.	4.38	4.50	3.00	5.00	0.72	1.00
I found the system very cumbersome to use.	1.38	1.00	1.00	5.00	1.02	0.00
I felt very confident using the system.	4.56	5.00	3.00	5.00	0.63	1.00
I needed to learn a lot of things before I could get going with this system.	1.50	1.00	1.00	4.00	1.03	0.25
Total SUS score	**83.91**	**87.50**	**65.00**	**97.50**	**10.33**	**18.13**

the equipment cost is one of the most frequently pointed out factors [25].

4. Conclusion

Learning where to place and how to incline a dental implant is crucial to guarantee optimal surgical outcomes and reduced intra-operative risks. In this study, we designed and developed IMMPLANT, an immersive educational tool to assist 3D dental implant placement learning. We evaluated our VR system that complements conventional implant planning interfaces by improving user interactions via the use of a smartphone. Participant feedback from the conducted usability and user tests clearly indicate that IMMPLANT enhances 3D visualization and manipulation of 3D dental content (in this case, lower jaw and virtual implant) as VR provides users with an immersive experience, with enhanced camera control and 3D perception, while hand interaction provided manipulation freedom and valuable geometrical information. In our evaluation, we found that users were receptive to the innovations brought forth by our work. The ability to preoperatively repeat the procedure and self-assess the work done on a VR system could help users gauge the quality of their work and determine skills to improve.

Regarding future improvements to the system, participants in our evaluation suggested that the smartphone interface can be improved, in particular, that the directional pad interface should explicitly indicate which geometric transformation is being applied, and also that measuring tools need to be implemented given that distance and angle measurements are essential for successful implant planning and surgical outcome.

Summary points

What is already known on the topic?

- Tools for improving the training and learning of dentistry students are required.
- Lack of training can negatively affect implantologists' performance during intraoperative procedures.
- Virtual environments could help to enhance 3D visualization and manipulation of anatomical content.
- Works focused on VR and AR in implant placement learning are scarce.

What does this study add to our knowledge?

- A Virtual Reality system to assist implant placement learning.
- Implants can be virtually placed into their ideal positions according to reversely planned implant-based rehabilitations.
- Free-hand interaction provides additional degrees of freedom and valuable geometrical information.
- A study on user acceptance with dentistry professionals.

Acknowledgments

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.ijmedinf.2020.104342.

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CHAPTER 4

USABILITY, ACCEPTANCE AND EDUCATIONAL USEFULNESS STUDY OF A NEW HAPTIC OPERATIVE DENTISTRY VIRTUAL REALITY SIMULATOR

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Usability, acceptance, and educational usefulness study of a new haptic operative dentistry virtual reality simulator

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ABSTRACT

Background: Dental preclinical training has been traditionally centered onverbal instructions and subsequent execution on phantom heads and plastic training models. However, these present present limitations. Virtual Reality (VR) and haptic simulators have been proposed with promising results and advantages and have showed usefullness in the preclinical training environment. We designed DENTIFY, a multimodal immersive simulator to assist Operative Dentistry learning, which exposes the user to different virtual clinical scenarios while operating a haptic pen to simulate dental drilling.

Objective: The main objective is to assess DENTIFY's usability, acceptance, and educational usefulness to dentists, in order to make the proper changes and, subsequently, to test DENTIFY with undergraduate preclinical dental students.

Methods: DENTIFY combines an immersive head mounted VR display, a haptic pen in which the pen itself has been replaced by a 3D printed model of a dental turbine and a controller with buttons to adjust and select the scenario of the simulation, along with 3D sounds of real dental drilling. The user's dominant hand operated the virtual turbine on the VR-created scenario, while the non-dominant hand is used to activate the simulator and case selection. The simulation sessions occurred in a controlled virtual environment. We evaluated DENTIFY's usability and acceptance over the course of 13 training sessions with dental professionals, after the users performed a drilling task in virtual dental tissues.

Results: The conducted user acceptance indicates that DENTIFY shows potencial enhancing learning in operative dentistry as it promotes self-evaluation and multimodal immersion on the dental drilling experience.

Conclusions: DENTIFY presented significant usability and acceptance from trained dentists. This tool showed to have teaching and learning (hence, pedagogical) potential in operative dentistry.

1. Introduction

The educational setting in dentistry traditionally involves two stages [1]: 1) theoretical schematic representation of the procedures to be performed; and, 2) their training on models, to mimic future application in supervised real clinical cases.

Initially, dental education was taught and trained in real tissues, such as removed teeth [2]. In 1894, phantom heads were firstly introduced and became the educational cornerstone in Dentistry [3]. Since then, they have permitted the recreation of theoretical clinical conditions after verbal and visual instructions on their execution. Nevertheless, these models lack realism, diversity as to pathologies and universal evaluation criteria thus contributing to subjective monitoring and grading [4]. The supervision of this type of educational approach is time-consuming and may be jeopardized by inadequate student/tutor ratio [5].

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As an alternative to these conventional training models, VR was introduced for dental training, providing superior tutoring aptitudes during students performance [6,7]. Virtual reality (VR) refers to technology that codes and compiles computer generated multisensory data to be perceived by users as alternative realities, allowing them to immersively interact with simulated tasks, events or scenarios frequently using head mounted displays. The growing use of simulation in healthcare, using VR technologies that mimic clinical reality, allows repetition and has been proven to add competence in health care providers, thus increasing performance in the clinical process and, therefore, increasing predictability and improving patient outcomes [8].

To increase the immersion and realism of the VR simulation, haptic technology has been proposed and used simultaneously in dental training [9]. Haptics is defined as the science of applying touch (tactile) sensation and control to interaction with computer applications [10]. A haptic training simulator is a computer based simulator enhanced with force (resistance to progression) and tactile feedback. Haptic experience contributed to advance the students' stage in the learning curve when later confronted with real scenarios [11].

Regarding the different dental specialties, several virtual models have been shown to increase learning skills in periodontal diagnosis and treatment [1], endodontic access cavities [12], oral surgery [13] and also for training regional blockage of the inferior alveolar nerve (proven to be adequate in several clinical parameters such as depth, anatomical location of the puncture, and resistance to progression) assisted by virtual tissue resistance [14].

Considering Operative Dentistry, haptic simulation may be decisive given the tactile complexity of the motor skills to be developed, namely resistance to the progression of cutting instruments offered by different elements (enamel, dentine, pulp, restorations and caries) with different degrees of mineralisation and density. Urbankova et al. [15] reported that the use of operative dentistry simulators at early stages of preclinical teaching improves student performance. Additionally, haptics and VR training resulted in greater learning efficiency, more hours of preclinical practice and allowed for more assessments per hour than students trained on traditional models in the University of Pennsylvania [16]. Also, fifth-year students from the Tokyo Medical and Dental University required less supervision by faculty members and showed greater skills [17].

We developed DENTIFY, a pedagogical multimodal immersive educational simulator, with the aim of recreating the cavity preparation phase inherent to operative dentistry, in a virtual environment. Contrary to other Operative Dentistry dental virtual reality simulators, DENTIFY includes the simulation of caries removal on more than one tooth (depending on the degree of difficulty established for the given exercise), and it already includes a multisensory stimulation by incorporating visual, tactile and auditory stimuli in the VR environment. It also allows for exercises to occur in two different modes: training mode and evaluation mode, although only the training mode was tested on dental professionals as a co-design strategy for future versions of DENTIFY. It is our objective to futher include full arch simulation exercises, soft tissue presence, bimanual handling and emergency scenarios.

Our goal is to verify if DENTIFY can positively assist teaching and learning experiences for cavity preparation tasks. In order to evaluate the educational usefulness, usability, and user acceptance of DENTIFY's interactive features, we conducted a user-study with professional dentists.

2. Materials and methods

2.1. Concept

DENTIFY is a tech probe aimed at assessing the user's perceived usability and educational potential by immersing a user in a virtual environment composed of visual, auditory and haptic stimuli. Combining a haptic pen, VR headsets, dental turbines drilling sounds, patient-specific teeth models and a laptop, its intention is to be a pedagogical tool with applicability in dental students' preclinical training environment.

Regarding the aforementioned preexisting simulators, we added 3D sound and an haptic device in which the pen itself has been replaced by a 3D printed model of a dental turbine. Furthermore, DENTIFY allows to simulate more than one cavity type in adjacent teeth (involving one or two dental surfaces). To ease the transition from the preclinical phase to the clinical university reality of operative dentistry, a virtual environment of the execution of a dental cavity was built.

2.2. Visual component

We resorted on the Oculus Quest 256GB that provided the visual immersive modality. Participants remained seated at a desk and used a haptic pen to perform cavity preparation tasks.

2.3. Apparatus and software

Our setup resorted on a laptop computer (Intel® Core^{TM} i7.8750H CPU, 2.20GHz 2.21GHz Processor, 512GB RAM, 1TB HDD, NVIDIA GeForce RTX 2060) running Windows 10 x64 bits. DENTIFY was developed and coded with Unity 3D (version 2021.1.0) using the C# programming language. Integration with Virtual Reality was done using the XR Interaction Toolkit plugin. Regarding the integration process of the haptic pen with the simulator, we used the Openhaptics® Unity Plugin developed and maintained by 3D Systems (Fig. 1). The integration of the haptic device (3D Systems Touch Haptic Device) makes it possible for users to manipulate, touch and to deform virtual objects. Additionally, it also allows to configure the resistance offered as well as the vibration level. The integration process of the haptic pen with the simulator uses the 3D Systems Openhaptics® Unity Plugin, developed and maintained by 3D Systems. The touch haptic device allows the user to freely move the device in the x, y and z axes. Although there is a maximum limit on the range of movement, namely position/sensing input 6 degrees of freedom, this limit is sufficient to replicate the use of a turbine. It also allows a feedback force of up to 3.3N. Force feedback was provided by a PHANToM Omni (SensAble Technologies) that is considered an admittance-controlled device [18]. The collision between the tooth's mesh and the virtual drill was detected using a simple raycast technique (ray-triangular mesh intersection): the virtual drill emits a ray from its tip (raycast); once the ray intersects a triangle of the tooth mesh, and if the distance between the drill and the mesh is below a small threshold, then the mesh is instructed to deform at the point of intersection and the turbine's sound changes to represent the drilling of dental tissue. In order to try to make the simulation more immersive and closer to reality, the removable part of the pen was replaced by a 3D printed replica of a dental turbine (Fig. 2).

2.4. Auditory component

The audio added to the simulator was obtained from real sounds arising from the use of the dental turbine (high rotation

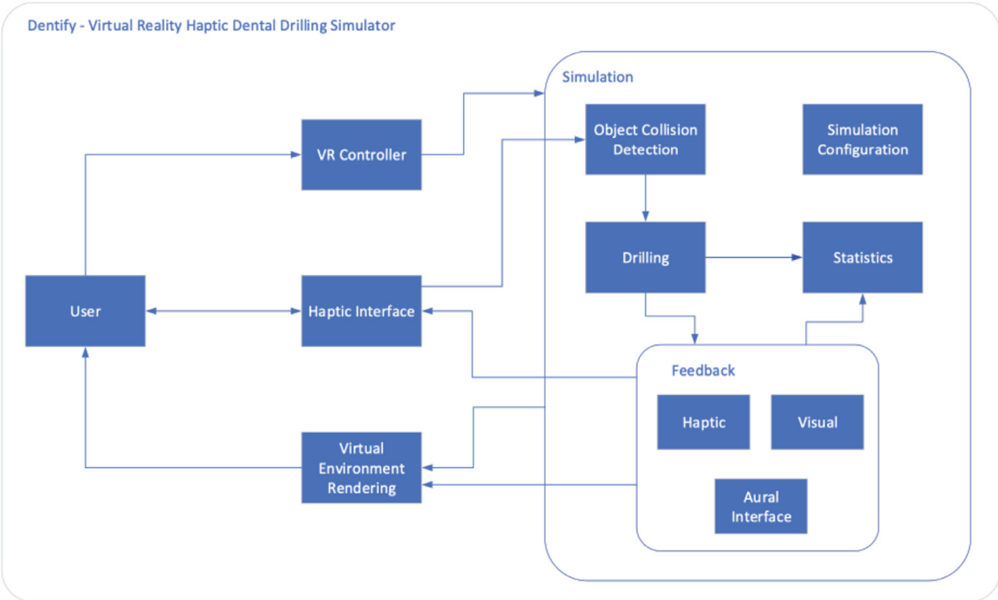

Fig. 1. System architecture.

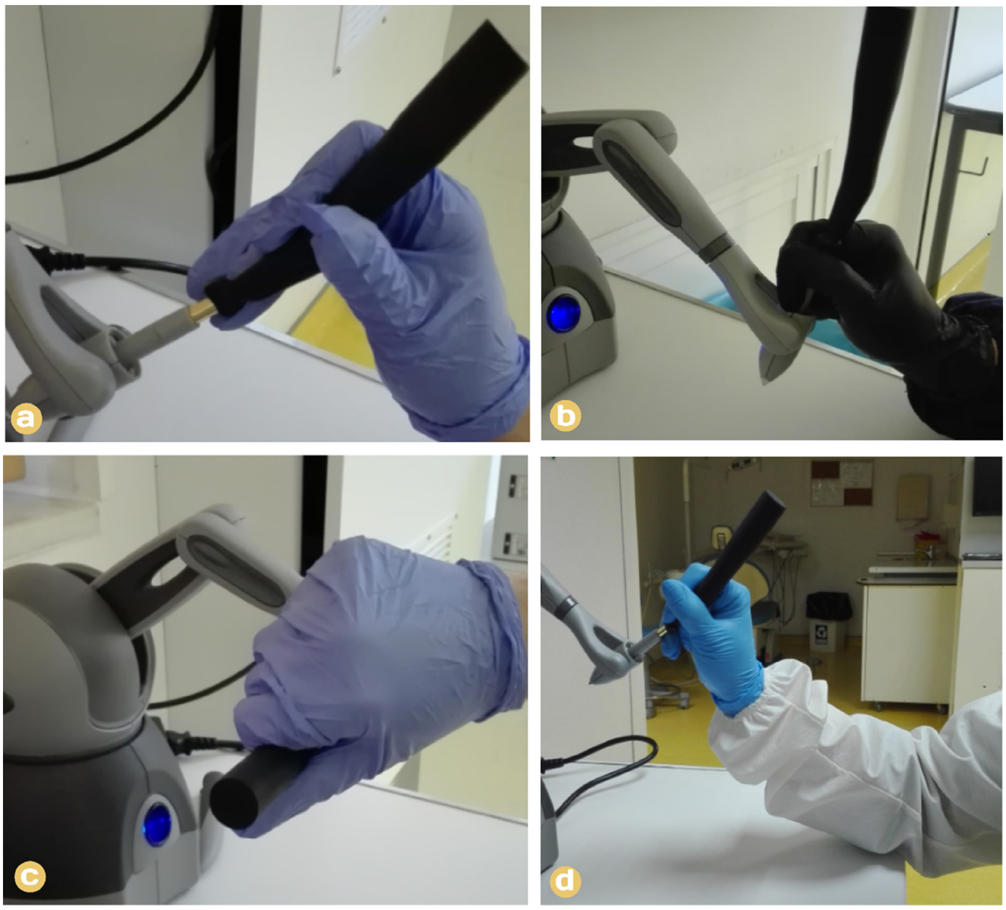

Fig. 2. Haptic pen handle. a) Haptic pen handle in the initial position. b) Haptic pen handle in adapted position. c) Haptic pen handle in unnatural position. d) Holding the haptic pen with arm support.

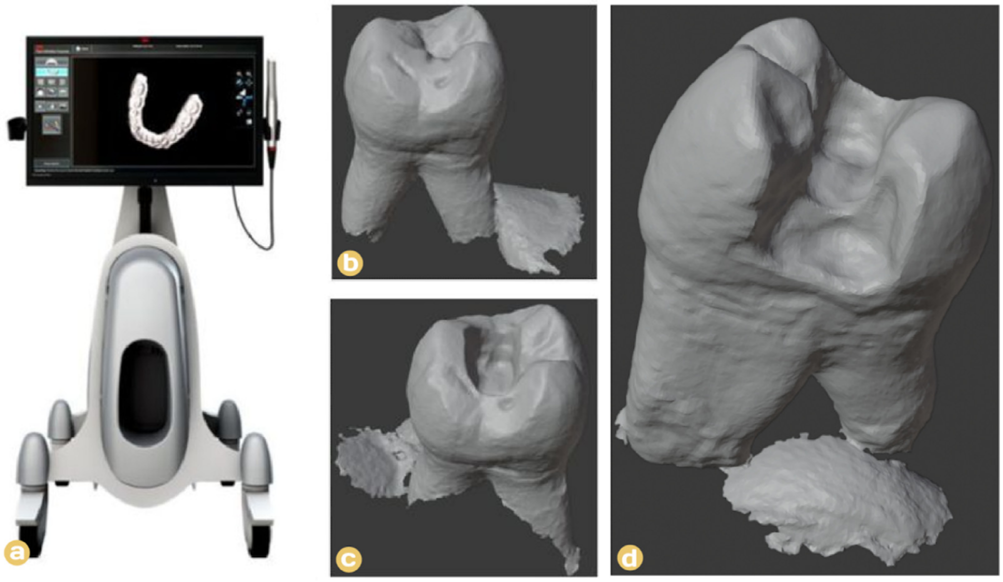

Fig. 3. 3D dental Scanner. a) 3M True Definition Dental Scanner. b) A 3D model of the healthy tooth. c) Tooth with a cavity on one dental surface. d) Tooth with a cavity on two dental surfaces.

instrument). A low-pass filter was applied to the sound of the turbine, both without contact and with contact whenever the deformation occurs in order to achieve a different sound that's closer to the real one during the drilling phase.

2.5. 3D Image data

A healthy molar tooth (freely donated to the Human Tooth Bank at Egas Moniz Dental Clinic) was scanned using an intra-oral scanner (3M True Definition, 3M Oral Care) (Fig. 3). The final virtual molar served as the basis for all exercises in the simulator. The same tooth was then prepared using a dental turbine and a spherical burr, obtaining a tooth with a cavity on the occlusal surface (Class I cavity). Then, the cavity was further drilled into an interproximal tooth surface (Class II cavity). Each of these cavity preparations was scanned. The scans generated STL files, which were then manipulated using a 3D modelling open source software (Blender, Amsterdam, Blender Foundation). The models had a very good level of detail and virtually no flaws in the virtual dental crown. The scans resulted in models with approximately 30,000 vertices. We relied on conventional surface rendering (Blinn-Phong shading of mesh triangles). No volume rendering was considered for rendering purposes.

Three anatomical structures were modeled this way: healthy tooth; tooth with a cavity on 1 tooth surface; and tooth with a cavity on 2 dental surfaces. To obtain the limits of both cavities, classes I and II, the model with the cavities was overlapped with the model of the tooth without deformations. After the limits of the respective cavities were properly extracted, it became possible to associate the class one or class two cavity limits to the original tooth..

2.6. Simulation environment

The simulation takes place in a virtual environment and is complemented with the haptic device, the virtual reality headsets, the corresponding controllers, and a laptop. It is possible to configure the simulation environment, ie, to choose the number of teeth in the simulation (1 or 2 teeth because the models created either only have the tooth to be deformed or have a tooth adjacent to the tooth to be deformed), and to select the type of cavity to prepare; namely, a class I (affecting 1 dental face) or class II cavity (involving 2 dental surfaces). The user can also indicate which hand is dominant. In this study, the user was able to choose only the dominant hand, since all other options were previously selected by the instructor.

In the task execution stage, a panel is displayed in the virtual environment containing the exercise description, where the aural interface will read the exercise description, which varies according to the cavity being prepared. Execution begins when the user clicks the OK button. A timer is displayed and, once it starts, the user will immediately see part of the turbine, the tooth to be deformed and a replica of the tooth to be deformed. To interact with the panel, the user can use the non-dominant hand to manipulate the controller (Fig. 4).

It is possible to return the tooth to its predefined position after starting the exercise. The user can choose between two types of drills with different diameters. Both drill models were created on the Blender software.

The next step of the simulation will be to prepare a cavity based on the description presented by the simulator. To perform the deformation, the user only needs to manipulate the haptic pen as if they were manipulating a dental turbine and bring the tip of the virtual drill close to the tooth surface to perform the drilling.

Once the user exercise is finished, the user should click Terminate and the haptic pen is deactivated (Figs. 5 and 6).

2.7. Participants

For this study, 13 unpaid participants were selected, of which 6 were female and 7 were male, with ages ranging from 24 to 38 (Median = 25, SD = 4,77) (Fig. 7). All participants were dentists. Their average experience, in years, is of approximately three and a half years. The minimum reported time working as a dentist was one month and the maximum was 14 years (Fig. 8). None of the participants reported having ever used a haptic pen.

2.8. Tasks and procedure

The study describes the simulator's evaluation. Each testing session involved the following steps: (I) completion of informed con-

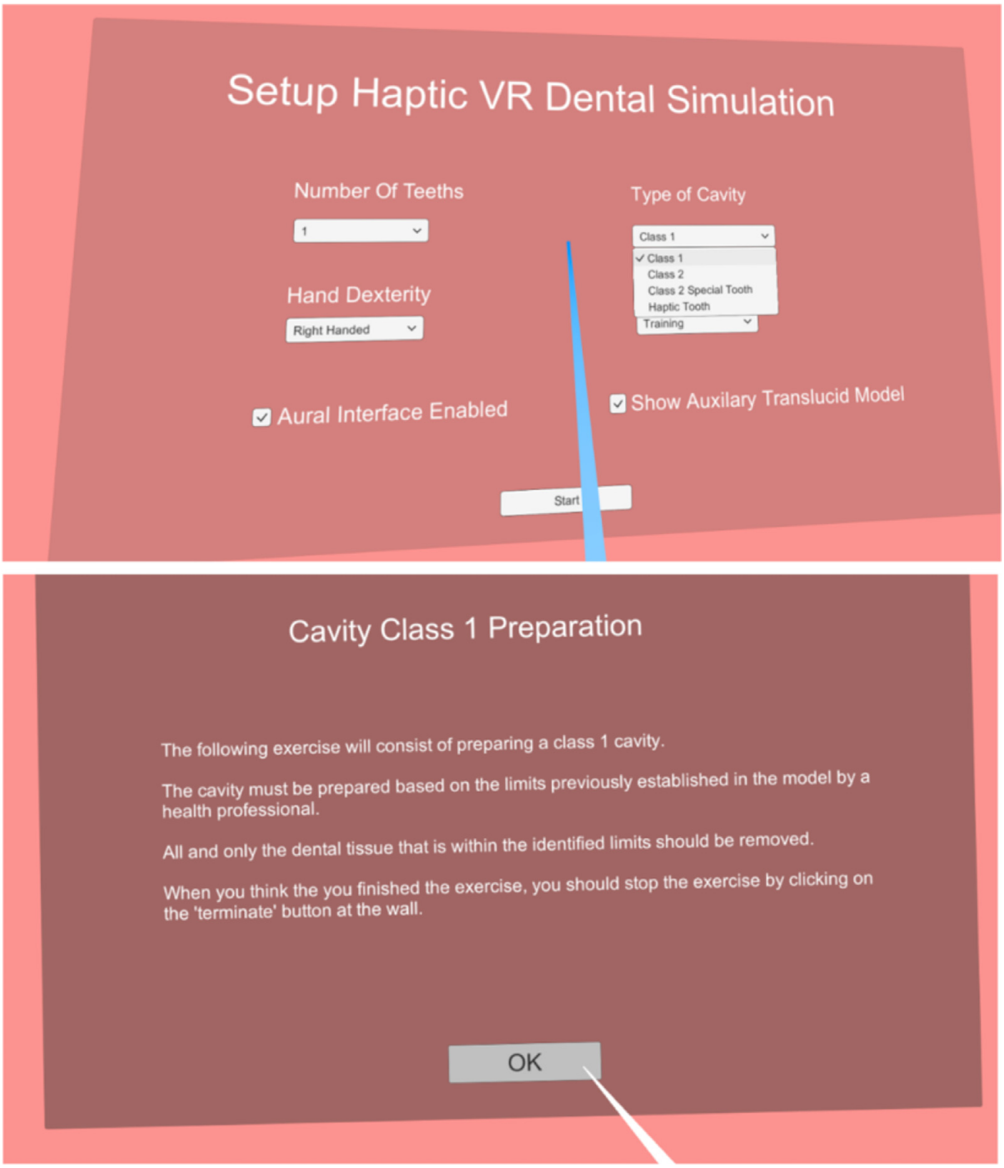

Fig. 4. Panels presented in the virtual environment for configuration and exercise description.

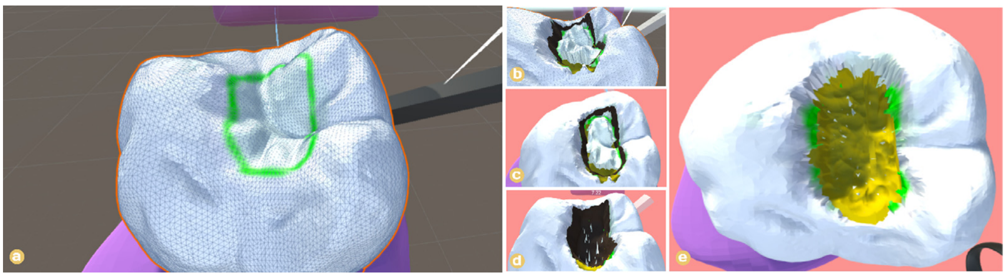

Fig. 5. Cavity Preparation. a) Initial Situation. b) Evolution of the Cavity Preparation. c) Occlusal view. d) Final Aspect of the cavity – cavity limits in brown. e) Occlusal view of Class I cavity preparation without the predefined cavity limits.

sent, (II) completion of demographic questionnaire, (III) introduction to the prototype, (IV) free experimentation, (V) execution of the tasks, (VI) completion of questionnaires associated with the experiment, and (VII) guided interview (Fig. 9).

The experiment-related questionnaires were: 1) Cyber Sickness Questionnaire (17); 2) SUS (System Usability Scale) Questionnaire and 3) NASA-TLX (NASA Task Load Index).

The NASA-TLX questionnaire aims to evaluate the workload felt by each participant during the drilling task. It includes six questions focused on the following: mental effort, physical effort, time effort, performance and frustration levels. It ultimately aims to assert user perception during the task completion experience. The SUS questionnaire measures the perceived usability of an interactive system; in our case, a dental simulator to perform virtual

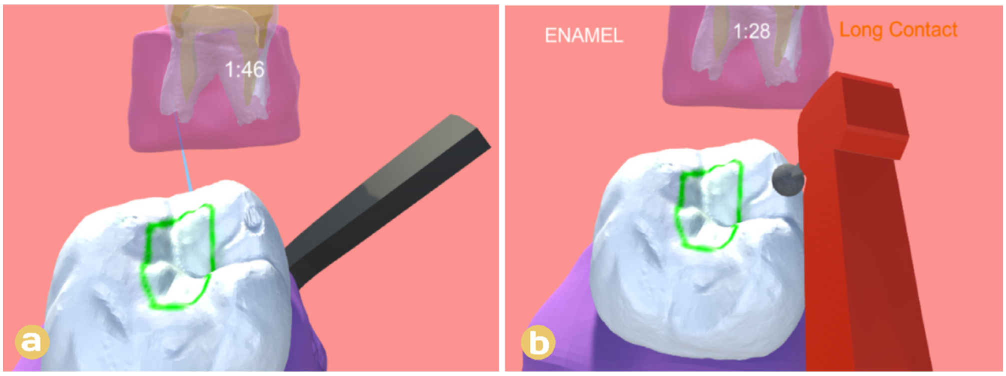

Fig. 6. Different status of the floating panels. a) Task timer on the floating panel. b) Full floating panel: center: timer; left: virtual tissues being prepared; right: prolonged contact warning.

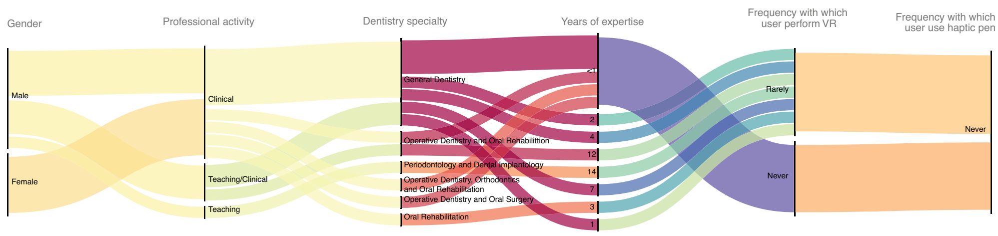

Fig. 7. Alluvial diagram summarizing the demographic data from profiles included in the evaluation.

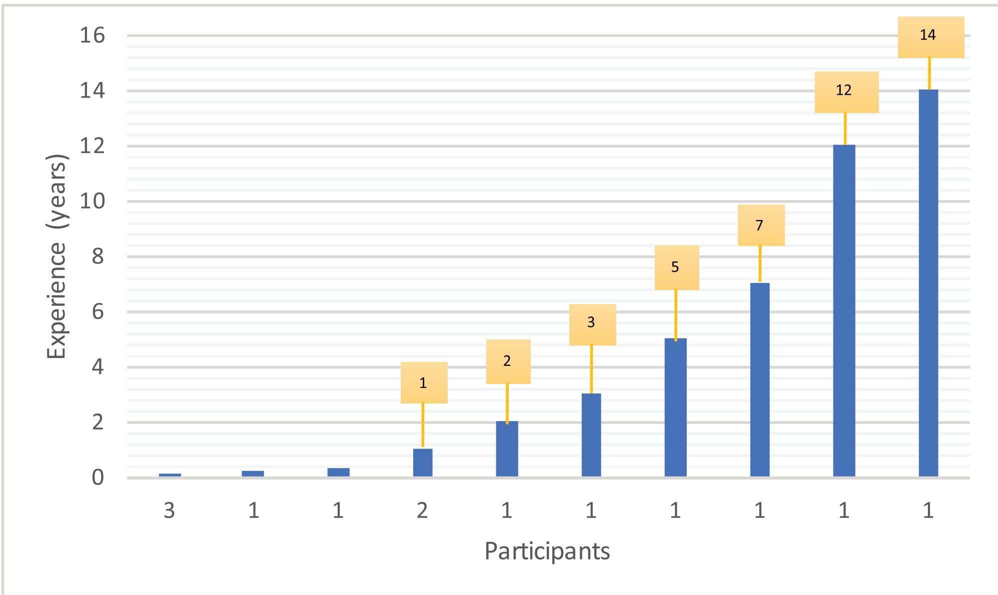

Fig. 8. Participants' professional experience.

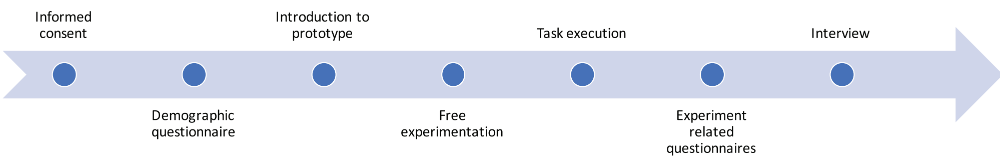

Fig. 9. Evaluation steps.

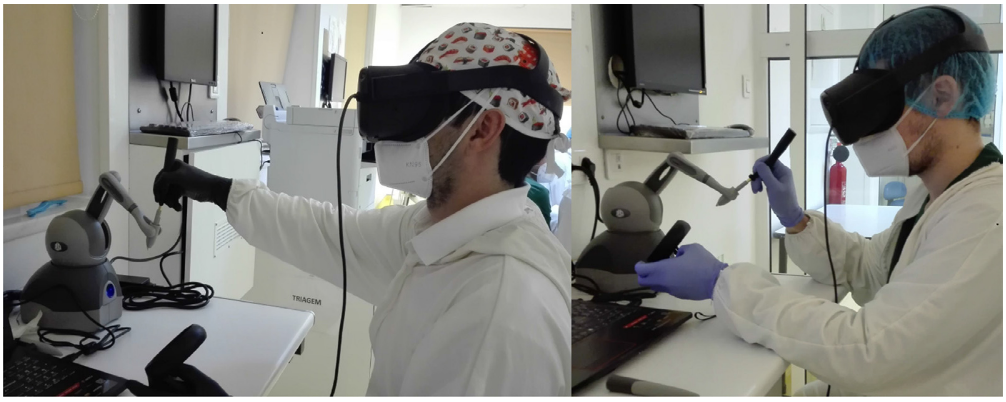

Fig. 10. Participants during an assessment evaluation session.

drilling tasks. Participant feedback was obtained through structured questionnaire or post-experiment interview-debriefing, regarding the limitations and benefits of the proposed interaction techniques.

The drilling task consisted of preparing a class 1 or class 2 cavity. Each user took an average of 1 h and the simulator assessment exercise took an average of 10–15 minutes. All the test sessions took place in a clinical environment at Egas Moniz Dental Clinic, namely under the supervision of C.i.i.E.M. (Centro de Investigação Interdisciplinar Egas Moniz, Monte da Caparica, Portugal) members.

2.9. Statistical analysis

The SUS scale score ranges from 1 to 100 and 68 points is considered the average score, according to a wide evaluation on several systems. The scores of the 10 items were transformed into a summary score ranging from 0 to 100, wherein the higher the value, the more user-friendly is proved to be. The scores are not percentages and should be considered only in terms of their percentile ranking.

Regarding NASA-TLX results, we considered the raw scores.

As for the cybersickness questionnaire results, they were obtained by calculating median and interquartile ranges responses. The gathered data were analysed using Microsoft Excel® statistical tools.

2.10. Hygiene and safety

To use the DENTIFY device, the user needs to make several physical contacts with the simulator, namely 3 points of contact. Additionally, the assessment tests needed to be performed during a pandemic, namely the COVID-19 pandemic, thus making it necessary to ensure all hygiene and biosafety conditions for the tests.

All testing sessions took place in a clinical environment at Egas Moniz Dental Clinic. Therefore, all participants were equipped with P.P.E. (Personal Protective Equipment), a KN-95 mask covered with a surgical mask, latex or nitrile gloves and a disposable or autoclavable cap (Fig. 10).

3. Results and discussion

3.1. Cybersickness

Regarding the Cybersickness questionnaire, participants reported only mild effects. The most frequently reported results were: slight headache in 7.69% (1 user), visual fatigue in 23.08% (3 users), difficulty maintaining focus in 15.38% (2 users) and blurred vision in 2 cases (15.38% of cases). These were attributed to fogging of the glasses due to air leakage in the nasal adaptation of the mask.

3.2. System usability scale

The highest reported score was 90 points and the lowest 62.50 points. Based on the responses, the system's average usability score was 77.50 points, with a standard deviation of 8.43 points (Table 1). The results are, therefore, 9.5 points above the average score of 68 defined by the scale.

3.3. NASA-TLX

The standard deviation was 14.7%, which suggests that there is some disagreement in the results, however not at an extreme level. From the graph, one can see that one participant had a rather high perception of workload, 77% of 100%. Compared to the minimum value of 20%, there is a considerable discrepancy between the lowest and the maximum reported values. There were, however, participants who were able to better adapt to the simulator and its limitations, displaying higher tolerance for experimental prototypes.

The time factor generated the highest discrepancy, with less experienced participants generally indicating that the exercise time corresponded to the time of a similar preparation on a real tooth, while more experienced participants indicated the opposite (Fig. 11). The physical fatigue presented was correlated with the absence of a resting point for one finger of the dominant hand, even though there was a support for the arm. However, all participants were able to prepare the proposed cavities. On average, users feel that it takes some effort to memorize control functionalities and ascertain the best position to perform the deformation, which can be correlated with non-existing previous experiences using haptic devices.

3.4. User experience

According to the feedback received, all participants indicated that they had a positive experience with the simulator. A slight learning curve was noted to be necessary since most participants reported an increasing ease of handling the simulator components as they approached the end of the task, suggesting a relatively short learning curve.

We considered the presented load index results to be relatively high because this study consisted mostly of experts who only used the system once and with no previous experiences using haptic devices. Also, we expect that the workload levels tend to decrease by increasing repetition.

Table 1
Descriptive statistics of SUS items: median, minimum value - Min, largest value - Max, interquartile range - IQR.

SUS item	Median	Min	Max	IQR
I think that I would like to use this system.	4.00	3.00	5.00	0.00
I found the system unnecessarily complex.	1.00	1.00	3.00	1.00
I thought the system was easy to use.	4.00	2.00	5.00	1.00
I think that I would need the support of a technical person to be able to use this system.	3.00	1.00	5.00	3.00
I found the various functions in the system were well integrated.	4.00	4.00	5.00	1.00
I thought there was too much inconsistency in this system.	1.00	1.00	4.00	2.00
I would imagine that most users would learn to use this system very quickly.	4.00	3.00	5.00	1.00
I found the system very cumbersome to use.	2.00	1.00	4.00	1.00
I felt very confident using the system.	4.00	3.00	5.00	0.00
I needed to learn a lot of things before I could get going with this system.	1.00	1.00	4.00	1.00
Total SUS score	**77.50**	**62.50**	**90.00**	**15.00**

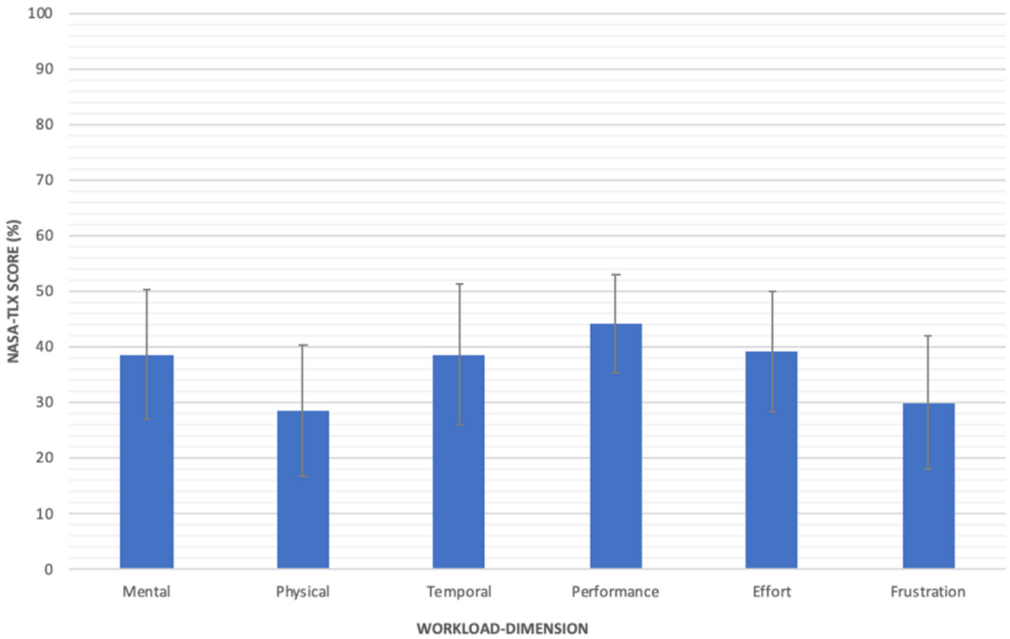

Fig. 11. NASA-TLX workload analysis results.

Table 2
Descriptive NASA-TLX workload dimensions: median, minimum value - Min, largest value - Max, interquartile range - IQR.

Workload dimension	Median	Min	Max	IQR
Mental	30.00	10.00	75.00	35.00
Physical	25.00	5.00	75.00	30.00
Temporal	40.00	5.00	80.00	37.50
Performance	40.00	20.00	65.00	37.50
Effort	45.00	10.00	70.00	35.00
Frustration	30.00	5.00	90.00	22.50

Although tactile sensitivity is subjective, all participants noted that they were able to feel the different resistance offered by the haptic pen on different virtual mineralised dental tissues and mentioned detecting differences between the progression resistance offered by the pen on virtual enamel and dentin. Overall, they reported that the drill's progression resistance in virtual enamel is approximate to that in real enamel, but considered the resistance offered to the virtual burr's progression in virtual dentin to be slightly excessive.

Users reported that there is still a noticeable learning curve when introducing students to the university clinic environment, and are of the opinion that familiarisation with a virtual clinical procedure scenario may help to mitigate difficulties inherent to this transition.

Participants mentioned that this exercise format is ideal for an initial phase of cavity preparation training, and that, at a later stage, the simulator should present an arch as opposed to only one or two teeth together, as well as include the presence of tongue, indirect vision and finger rest support. The initial phase of cavity preparation training for undergraduate teaching refers to the first learning stages that a preclinical dental student must undergo in operative dentistry, more specifically drilling using a dental turbine with an attached burr for cavity removal. In this context, traditional learning methods for preclinical dental students involve drilling on plastic teeth on phantom heads with theoretically described cavities. In our study, participants considered that the simulator adequately replicates the educational and pedagogical requisites for competence acquisition in this early phase of operative dentistry training. This first version of DENTIFY already incorporates metrics for automatic feedback on the trainee's performance which, undoubtedly, are powerful assessment tools on the students' performance (both self and tutor assessments). Such metrics include, for example, the total time spent performing the task (simulation time), drill elapsed time, average contact with simulated dental tissues in seconds, number of prolonged contacts, amongst others. The simulator also allows for users to save their data per user and per simulation, thus allowing to compile the user's graphical progressive evaluation. However, the present study aimed to evaluate user acceptance amongst trained dentists in a co-design phase, which allowed us to create a version 2.0 of

DENTIFY. We intend to test this newer version with dental undergraduate students and apply those metrics to evaluate personal performance and, consequently, further pedagogical value of the simulator.

All experts adhered well to the experiment, even mentioning that the use of virtual reality can help increase students' curiosity and interest, as well as serve as a pedagogical tool for exploration and acquisition of new skills. That said, the participants considered adopting and generalising the use of this type of technology as a complement to traditional training techniques.

3.5. Future work

This study's purpose was to introduce DENTIFY version 1.0 to experienced dental professionals to assess its pedagogical value and to obtain information regarding alterations it must undergo to better translate clinical day to day practice, thus reducing the distance between preclinical and clinical environments. In this context, DENTIFY's main limitations have been identified and further work must consider, for instance: adding more clinical simulated cases, bimanual manipulation including mirror and indirect vision, adding a finger resting point (for the dominant haptic device controlling hand), the creation of emergency scenarios and including both full dental arches. Although these limitations have been identified and are, currently, being worked on DENTIFY 2.0, version 1.0 presents some differentiated features, as already mentioned.

Besides the previously mentioned immersive multimodal simulation and multiple teeth training scenarios, DENTIFY's training mode and a simulation mode differ on the technical difficulty level of the presented task and also on the different adjustable settings between in each mode (which will be subject to future work). The study presented on this paper used only the training mode. Also, another main difference we can report is that the task exercises used to test version 1.0 were obtained from real human models, as described earlier in subsection 2.6. The authors believe that reducing the gap between simulation and clinical reality will ease the transition from preclinical undergraduate simulation into clinical reality. The use of real models is of our utmost priority. This way, we intend to collect real cases obtained at Egas Moniz Dental Clinic and, anonymously, convert them into simulation models so that undergraduate preclinical students can be exposed to a wide range database of real simulated clinical situations that dentists deal with on a daily basis. This will approach the pre-clinical student to clinical reality and, expectedly, increase treatment predictability and decrease human errors.

It is our objective to test DENTIFY V2.0 with undergraduate students and, hopefully, to incorporate these type of simulators in dental teaching, not only in Operative Dentistry but also in other areas of Dental Medicine. The authors consider that one of the main challenges for the developing dental simulators concerns their ability to translate real clinical scenarios into simulated ones. In other words, the realism of the simulation is a consequence of the realistic data added to the simulator. In this way, focus must be put on both visualization and touch feedback in order to improve realistic the inclusion of clinical cases to the training tasks and challenges of dental simulators.

One of the main limitations presented regarding the use of VR and, mostly, haptic technology is hardware and software costs. This must be considered when projecting the use of these technologies in dental schools, mainly in developing countries and schools with numerous students, for example. Further work must be put on simulators to prove their unequivocal benefit in terms of pedagogical advantage and, also, to make them more affordable since this can place some financial stress on dental schools. However, one must also consider the cost of creating rooms with numerous individual work posts equipped with compressed air, the hardware and logistics necessary to make these rooms a reality and, ultimately, the costs of the plastic models needed to perform classical dentistry teaching.

In this study, participants presented physical health and had no relevant issues that could affect the use of VR headsets. We agree that the presence of physical impairments could compromise their performance and, also, the results. This must be taken into consideration when the intention is to make these technologies generally accessible in dental schools. We emphasize that visual impairments are normally corrected by spectacles or contact lenses (it may be interesting to explore whether these corrective measures impact performance) and the probability of undiagnosed visual diseases is seldom. As such, we will consider this possible confounding variables in future tests.

4. Conclusion

The introduction of haptic technology and Virtual Reality (VR) have added new dimensions to education and the approach to daily professional challenges. Simulation in healthcare has been focused on both clinical and educational aspects. The fast growing pace of these technologies must be accompanied with clarity and objectiveness. Further debate is necessary to adress and clarify such studies, such as the guidelines proposed by Cheng et al. [8].

In Health education, the approach paradigm to both patient and disease has changed. It is unequivocally intended that a training process that is closer to reality will allow for fewer complications arising from the medical act, greater predictability and lower morbidity.

Pre and postgraduate education in Dentistry require an evolutionary break; a qualitative leap, in line with the real technological potential that we currently have. More predictable results are sought, exhibited by students with more training hours, and with the constancy of competence that comes from repetition. This is a real need and opportunity for Education, particularly applicable in the context of distance learning motivated by the pandemic. However, solutions closer to reality should be sought, based on feedback by professionals and teachers.

This study's results allow to conclude that DENTIFY was well accepted by this group of professional dentists who have also reported it to have usability, user acceptance and educational usfulness. Further studies are required to assess DENTIFY properties in Dental Education settings.

Credit author statement

All persons who meet authorship criteria are listed as authors, and all authors certify that they have participated sufficiently in the work to take public responsibility for the content, including participation in the concept, design, analysis, writing, or revision of the manuscript. Furthermore, each author certifies that this material or similar material has not been and will not be submitted to or published in any other publication before its appearance in the Computer Methods and Programs in Biomedicine.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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CHAPTER 5

PRECLINICAL DENTAL STUDENTS' SELF-ASSESSMENT OF AN IMPROVED OPERATIVE DENTISTRY VIRTUAL REALITY SIMULATOR WITH HAPTIC FEEDBACK

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Preclinical dental students self-assessment of an improved operative dentistry virtual reality simulator with haptic feedback

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To test and evaluate the second installment of DENTIFY, a virtual reality haptic simulator for Operative Dentistry (OD), on preclinical dental students, by focusing on user performance and self-assessment. Twenty voluntary unpaid preclinical dental students, with different background experience, were enrolled for this study. After the completion of an informed consent, a demographic questionnaire, and being introduced to the prototype (on the first testing session), three testing sessions followed (S1, S2, S3). Each session involved the following steps: (I) free experimentation; (II) task execution; S3 also included (III) completion of questionnaires associated with the experiment (total of 8 Self-Assessment Questions (SAQ)); and (IV) guided interview. As expected, drill time decreased steadily for all tasks when increasing prototype use, verified by RM ANOVA. Regarding performance metrics (Comparisons by Student's t-test and ANOVA) recorded at S3, in overall, a higher performance was verified for participants with the following characteristics: female, non-gamer, no previous VR experience and with over 2 semesters of previous experience of working on phantom models. The correlation between the participants' performance (drill time), for the four tasks, and user self-assessment evaluation, verified by Spearman's rho analysis, allowed to conclude that a higher performance was observed in students who responded that DENTIFY improved their self perception of manual force applied. Regarding the questionnaires, Spearman's rho analysis showed a positive correlation between the improvement DENTIFY inputs on conventional teaching sensed by students, also enhancing their interest in learning OD, their desire to have more simulator hours and the improvement sensed on manual dexterity. All participating students adhered well to the DENTIFY experimentation. DENTIFY allows for student self-assessment and contributes to improving student performance. Simulators with VR and haptic pens for teaching in OD should be designed as a consistent and gradual teaching strategy, allowing multiplicity of simulated scenarios, bimanual manipulation, and the possibility of real-time feedback to allow for the student's immediate self-assessment. Additionally, they should create performance reports per student to ensure self-perception/criticism of their evolution over longer periods of learning time.

Preclinical teaching in Operative Dentistry (OD) focuses on the development of manual dexterity, which is a keystone clinical skill exerted on a daily basis. Manual dexterity entails the development of motor skills inherent to the acquisition of necessary tactile complexity. An example consists of performing dental cavities with

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precision in tissues with different physical properties and, challenging enough, present unique resistance to the progression of cutting instruments applied on them.

The most used educational strategy in OD is based on 2 phases[1]: Phase (1) theoretical schematic representation of the procedures to be performed; and Phase (2) training on human models mimicking a real clinical scenario in a simulated environment. It is a goal of the simulation replay to reduce the discrepancy between training in an artificial pre-clinical environment and the real clinical environment. Historically, several methods have been used to promote the simulation and development of delicate manual movements inherent in OD, ranging from the use of real human extracted teeth[2] to what is considered the cornerstone of pre-clinical teaching in OD: the phantom heads. Introduced in 1894[3], these are three-dimensional fabricated models in which the student can replicate hypothetical clinical procedures by means of verbal and visual theoretical instructions in a simulated physical environment. Despite their undeniable historical importance, several issues have been pointed out pertaining to their use, namely the lack of realism and the potential subjectivity of the evaluation criteria applied to grade the works performed on them[4], as well as reduced variability of the simulated environment, in addition to the fact that this assessment can be time-consuming and hurt the student/teacher ratio leading to less time to assist students training[5].

Virtual reality (VR) with haptic capacities shows up as a promising technology for OD training. VR refers to technology that codes and compiles computer generated, multisensory data to be perceived by users as alternative realities, allowing them to immersively interact with simulated tasks, events or scenarios frequently using head mounted displays. Haptics is defined as the scientific discipline that studies the application of touch (tactile) sensation and control to interaction with computer applications[6]. Head mounted displays and Haptic Technology have been increasingly used in medical training and education bringing teaching simulation closer to clinical reality[7,8]. In Dental Education, several simulators have been developed for Periodontology[1], Endodontics[9], Oral Surgery[10], Prosthodontics[11] and Anesthesia[12], yet for OD there is still a gap, and the use of VR and haptic pens has shown promising preclinical teaching results[13–16] due to its positive impact on accelerating the learning curve and both manual dexterity and motor skills. Moreover, evaluation evidence indicates the usefulness of the haptic simulators in early dental training[15]. They complement the existing phantom head simulators by offering qualitatively different features[17]. There are several studies pertaining to the advantages that simulators add in sensory feedback, which provides better performance in real preparation of virtual enamel and dentin cavities, as well as those that unlimited repetition allowed by VR simulators and haptic pens have on the acquisition and development of psychomotor skills without the need for additional teaching staff[18–21]. A greater number of repetitions allows for faster development of motor skills and manual dexterity competences needed for OD[22]. Both practice through repetition and self-assessment lead to better performance in OD[23]. The models in use for teaching in dentistry are the so-called part-task trainers, ie, a model used to train one particular task and, therefore, to practice and improve one particular skill. In a way, these can be considered modular components of teaching/training which, by acceptance of a partial simulation, when combined, allow for adaptation of the total training system.

The introduction of novel digital technologies for OD teaching is, in 2023, an extensively studied subject. Digital solutions to OD teaching have already been previously tested and compared regarding traditional teaching methods and if, on one hand, the use of VR improves the satisfactory performance of students[15], on the other hand, although digital methods can be considered as a paradigm shift on dental undergraduate teaching, the human tutor factor cannot be disregarded even when both classical and digital methods show comparable results[24]. The decision on the timing of introducing digital technologies in dental teaching should be, therefore, taken with enormous sensitivity. In this newer version, besides improving the overall aesthetics of the previous version, DENTIFY II includes indirect vision via a virtual mirror, it allows for training virtual dental cavities in both individually isolated teeth or in teeth placed in the virtual mandible, as well as more system metrics for real time evaluations and self assessment..

In context with the aforementioned advantages resulting from exposing dental students to immersive VR haptic simulators (already demonstrated by other commercially available simulators, e.g., Simodont®, Virteasy®) we developed DENTIFY, a pedagogical multimodal immersive educational simulator, with the aim of recreating the cavity preparation phase inherent to OD in a virtual environment[25]. In this study, we present the second installment of the prototype. Combining a haptic pen, VR headsets, dental turbine drilling sounds, patient-specific teeth models and a laptop, DENTIFY aims to be a pedagogical tool applicable in dental students' preclinical training environment. The present DENTIFY version was updated and improved, after being previously tested by OD teachers[26]. The aim of this work is to test and evaluate the current version of the DENTIFY prototype on undergraduate (preclinical) dental students, by focusing on user performance and self-assessment.

Materials and methods

Concept. DENTIFY is an OD simulator that resorts to VR and haptic pen technology. It places the student/user in an immersive virtual environment, composed of visual, auditory and haptic stimuli. It combines a haptic pen, VR goggles with audio output, turbine and drilling sounds, virtual dental models of isolated teeth and complete dental arches. In order to promote realism of the virtual environment immersion, the haptic pen grip has been replaced by a printed model of a dental turbine. It is intended to be a pedagogical tool for training and teaching the cavity preparation phase in OD, aimed at students in preclinical training for the purposes of improving the student's manual dexterity and three-dimensional spatial manipulation, increasing the number of repetitions per training session, and, additionally, providing a set of metrics corresponding to each use, per user. The simulator also allows for users to save their data per user and per simulation, thus allowing the user to compile a graphical progressive evaluation. Exposing the student to DENTIFY's metrics results aims to stimulate self-assessment and self-criticism, as well as the perception of the user's own learning curve on the grounds of objective and measurable parameters.

As in the previous version[25], different virtual tissues have different degrees of resistance to in depth progression of the virtual drill. More specifically: virtual enamel offers high resistance to progression; virtual dentin offers intermediate resistance; virtual caries offer low resistance; and no resistance to progression when reaching the virtual pulp. There is the option of defining the virtual cavity boundaries or not. For this study, all tasks had defined virtual cavity boundaries.

The version presented in this study presents several add-ons to the previously published version, namely: allowing for more than one type of tooth cavity; realization of virtual cavities in both isolated virtual teeth or in their position in the virtual arch; the possibility of zooming on both isolated virtual teeth and complete virtual arches; indirect vision (including customization of the virtual mirror's size and, therefore, the depth of field and the dimensions of the reflected image (Fig. 1); and, as mentioned above, allowing for the collection of data pertaining to individual use, thus enabling an objective, numerical and measurable evaluation. Additionally, the new version of DENTIFY allows for three-dimensional manipulation of the individual tooth or virtual arch; allows for the selection of 4 types of virtual spherical drills (in this study, only one virtual drill of equal size was allowed to be used to standardize all users and tasks); and informs the student of the proximity and injury of virtual structures of the used tooth or neighboring teeth, during the simulation.

Visual, haptic, and auditory components. For the visual component, we resorted to a pair of Oculus Quest 256GB, which was strapped to the user's head while seated at a desk. Regarding the haptic component, touch feedback was provided by a haptic pen by 3D Systems Touch Haptic Device to perform cavity preparation tasks. Integrated sound speakers of the Oculus Quest provided audio feedback.

We recorded real sound from high rotation instruments in contact and without a dental structure to incorporate into the simulator. Following the recording, we applied a low-pass filter, whenever deformation occurred, to achieve a different sound that's closer to the real one during the wear phase.

Apparatus and software. Our setup consisted of a laptop computer (Intel®Core TM i7.8750H CPU, 2.20GHz 2.21GHz Processor, 512GB RAM, 1TB HDD, NVIDIA GeForce RTX 2060) running Windows 10 x64 bits. DENTIFY was developed in Unity3D (version 2021.1.0) using the C# programming language. Integration with Virtual Reality was done using the XR Interaction Toolkit plugin. To integrate the haptic pen with the simulator, we resorted to the Openhaptics®Unity Plugin, developed and maintained by 3D Systems . This integration, paired with adjustments to the resistance offered and to the vibration level, makes it possible for users to feel touch while manipulating and deforming virtual objects. The replication of the use of a turbine was possible due to enough movement and rotation freedom allowed by the haptic device and a feedback force of up to 3.3 N, provided by the admittance-controlled device PHANToM Omni (SensAble Technologies)[26]. This feedback force was activated whenever the virtual drill collided with the virtual tooth. To detect collision we used a simple ray casting technique (Ray/Triangle Mesh Intersection): the drill emits a ray from its tip (raycast technique); once the ray intersects a triangle of the tooth mesh, and if the distance between the drill and the mesh is below a small threshold, then the mesh is instructed to deform at the point of intersection and the audio emitted by the turbine switches to the sound of dental tissue being drilled. To make the participants feel more immersed in the training experience, a 3D-printed replica of a dental turbine was attached to the haptic pen (Fig. 2).

3D image data. The virtual molar that was used on all the exercises was the result of an intra-oral scan (using 3M True Definition, 3M Oral Care) of a healthy tooth freely donated to the Human Tooth Bank at Egas Moniz Dental Clinic. To obtain scans for different types of cavities (Class I and II), that same tooth was prepared using a dental turbine and a spherical burr, starting with a Class I cavity, and then expanding the compromised area to the interproximal surface to create a Class II cavity (Fig. 3). Each of the cavity preparations was scanned using the same method as the original tooth.

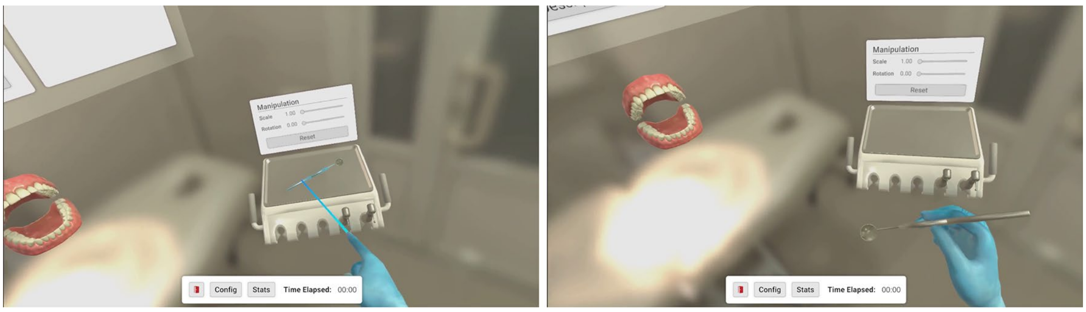

Figure 1. Tool selection process: using the controller, the user points their hand towards the instrument tray and at their desired tool. The selected tool is highlighted in blue and upon pressing the trigger is equiped in the user's hand. The user may press the cancel button to release the tool.

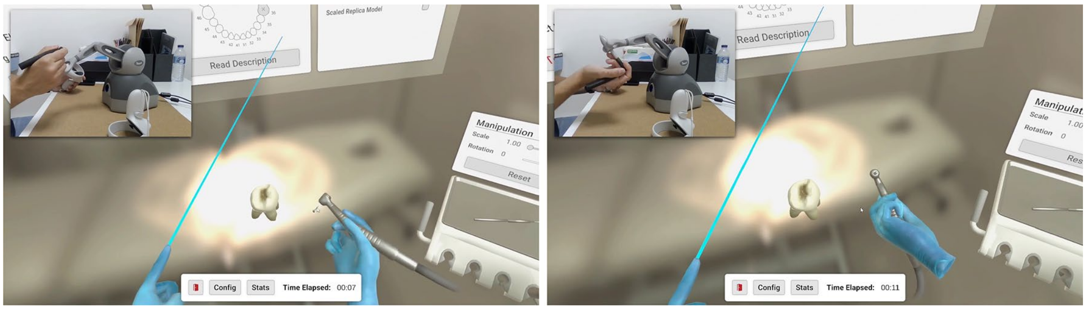

Figure 2. Haptic Pen and VR Controller combined workflow: using the haptic pen with their dominant hand, the user moves the drill, feeling force feedback and vibration. With their other hand, the user holds a regular VR controller that can be used to manipulate the environment, interact with the UI or operate auxiliary tools.

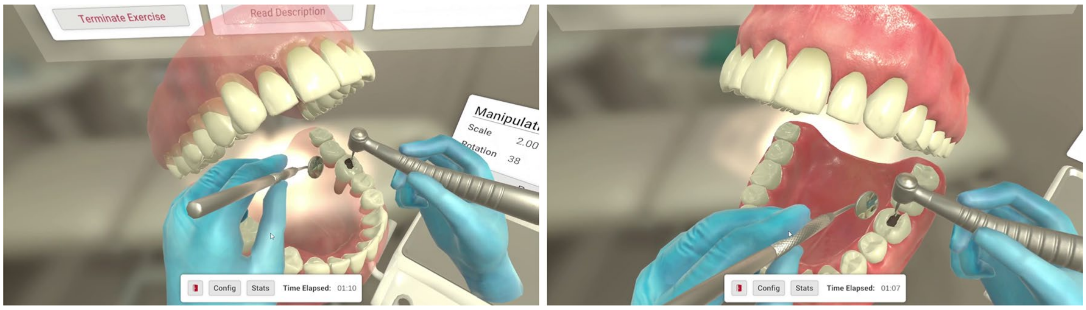

Figure 3. Different cavity types supported: on the left, a class 1 cavity, and on the right, a class 2 cavity. The denture model is scaled to double its original size and the drilling is executed with the help of a mirror for extra visibility. Additionally, the opacity of the Gums was turned down so the user could clearly see the root of the tooth.

These scans were further manipulated using a 3D modeling open-source software (Blender, Amsterdam, Blender Foundation) and saved as STL files. The final models were of great detail and accuracy and consisted of approximately 30,000 vertices.

We were able to model three tooth variations: a healthy one, a tooth with a cavity on one surface and a tooth with a cavity on two dental surfaces. Then, by overlapping the models with cavities with the healthy one, we were able to extract the limits of the cavities, which allowed us to show these limits on the healthy tooth.

The images are screenshots taken from the software developed solely by the authors for the purpose of this study. All the materials used in this software were created by us with the exception of the teeth and gums model which were published under a CC0 license and thus do not legally require attribution.

Simulation environment. The virtual simulation environment is provided by the VR headset and its controllers in conjunction with the haptic simulation device, all connected to the same laptop. There are some configurations available for the environment, such as the number of teeth in the simulation (either one tooth or a full set of teeth), the type of cavity (Class I, affecting one dental surface or Class II, involving two dental faces), and the user's dominant hand. These configurations are all done by the instructor.

Once the user moves to the execution stage, a voice starts reading the exercise description shown on a virtual panel in front of the user. This description depends on the type of exercise selected. To begin the exercise, the user must click the OK button, which displays a timer and reveals the tooth to be deformed and the turbine. To grab the turbine, manipulate the tooth or interact with the panel, the user can use the controller in their non-dominant hand. The manipulation of the tooth allows modification of its rotation, position, and scale (Fig. 4). On their non-dominant side, the user finds a tool shelf with four types of drills with different diameters and shapes. These models were created using Blender.

When the user is ready, they should click the Start Exercise button, which starts the timer and allows the drilling to begin. The tooth is deformed by making contact between the tip of the drill and the surface of the tooth, which is achieved by handling the haptic pen as if it were a real dental turbine. Whenever the user feels the deformation they performed matches the one described on the assignment, they should click Terminate Exercise. The timer then stops, and the haptic device is deactivated.

System metrics and task assessment. DENTIFY allows for the collection of various performance data pertaining to each user, per use. The collection of this data aims to establish an evolutionary curve of the student's learning over time, by comparing each session's results at different points in time. Additionally, it allows the student's performance to be broken down into numerically objective and measurable data, thus providing

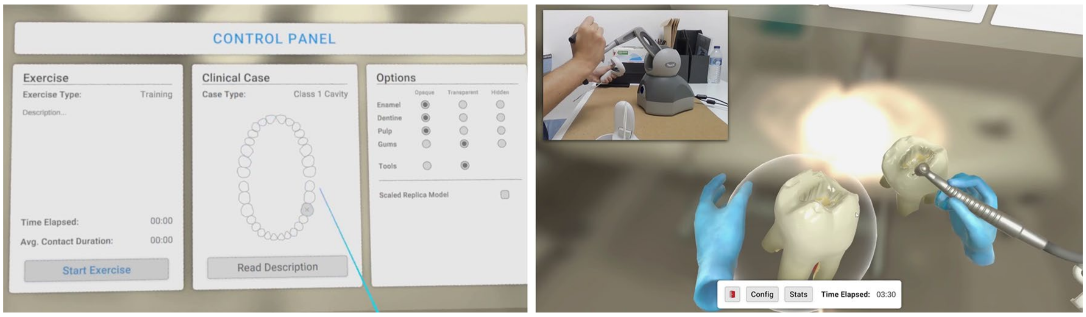

Figure 4. Optional settings: in training mode, the user is given a wide range of settings and information to complement the exercise. A text, visual and spoken description of the clinical case, metrics along with visibility options. The user may start the exercise whenever they are ready to begin. Scaled Replica model: optionally, the user can manipulate a large copy of the tooth in their non-dominant hand for referencing during the exercise.

the student with the possibility of self-assessment on each set criterion. The current version of DENTIFY has several evaluation parameters, and the following were considered: task execution speed (simulation elapsed time) and drill-tooth contact time (drill time). Additionally, it allows distinguishing three different types of contact between drill and virtual model: normal (less than 2 s), prolonged (between 2 and 4 s), and very prolonged (more than 4 s). These contacts can be measured independently in virtual enamel and dentin. During the task execution, the student is informed when contacts are prolonged and very prolonged by audio and chromatic stimuli. Similarly, DENTIFY informs the student of iatrogenic contacts with adjacent teeth (in simulations with the virtual tooth in its position in the arch), inadvertent contacts with the gingiva, and close pulpal contacts. DENTIFY aims to take full use of the full potential of self-assessment using 3 essential strategies: (1) by allowing users to measure the final results after a single task execution; (2) by comparing their evolution through time, thus establishing a growth curve; and (3) by including a digital real-time evacuation system (intra-operatory), namely the 3 level contact time between the virtual drill and the virtual model.

Participants. Twenty preclinical (3rd year) dental students were enrolled for this study. All participants agreed to participate voluntarily. None of the members of the research team had direct teaching responsibilities on the participants. Participants mean age was 22.0 years old and it was comprehended between 22 and 36 years. The group consisted of 14 (70%) females and 6 (30%) males. Regarding the previous experience with phantom heads and plastic tooth models, fifteen participants (75%) reported having two semesters of experience in performing dental cavities on phantom models as part of their OD classes while five participants (25%) reported having more than two semesters of experience. Additionally, 25% of the participants reported having performed between 10 and 15 dental cavities in flask teeth (i.e., models of plastic teeth inserted into plastic maxillae and/or mandibles), 25% reported having done between 15 and 20 cavities, 25% between 20 and 25 cavities and 5 participants (25%) reported having done more than 25 dental cavities in plastic models. When considering VR and Haptic Technology (HT) experience, 19 participants (95%) reported never having used a haptic pen, and 4 participants (20%) stated having previously experimented with VR. Five participants (25%) identified themselves as gamers.

Tasks and procedures. After the completion of informed consent and a demographic/user profile questionnaire, followed by a habituation task, participants were asked to perform three testing sessions (S1, S2, S3). Each session involved the following steps: (I) free experimentation; (II) task execution; and S3 also included (III) guided interview. The demographic/user profile questionnaire was conducted during the first session, prior to the free experimentation. Google Forms was used to collect the following data: (i) Gender; (ii) Age; (iii) Do you have experience with plastic models?; (iv) Is this the 1st year that you are using plastic models?; (v) How many cavities have you performed in plastic models during the preclinical Operative Dentistry teaching?; (vi) Have you ever experienced Virtual Reality?; (vii) Have you ever experienced Haptic Technology); and (viii) Are you a gamer?.

The guided interview was not conducted verbally. Instead, each participant was given a Google Docs document to answer two types of questions: free responses, quantitative analysis questions using the Lickert scale and close-ended questions: (1) The free response questions were: (i) What is your opinion on training with phantoms/plastic models?; and (ii) What do you consider to be the limitations of the current teaching method with phantoms and plastic models? (2) The quantitative analysis questions graded using a 5-point Likert scale were: (i) Did you feel that experimenting with the simulator contributed to improving traditional teaching/learning in preclinical Operative Dentistry?; (ii) Do you find that the simulator increased your interest in Operative Dentistry?; (iii) Would you like to have more hours of simulator training?; (iv) Do you consider you have a better manual perception of the force to apply in a dental turbine after training with DENTIFY?; (v) Do you think that training with the DENTIFY simulator can contribute to your 3D visual perception of the dental cavities?; (vi) In your experience, can the evaluations of some phases of the procedures in plastic models be subjective (two tutors evaluating the same result with different grades)?; (vii) Do you think your preclinical Operative Dentistry training can be more independent using DENTIFY?; (viii) Do you consider that a longer use of DENTIFY can further improve your manual dexterity?; (ix) Do you consider that the extended contact warnings contribute to your perception of the iatrogenic risk of overheating when performing a cavity? (3) The close-ended questions were: (i) What type of exercise did you find most relevant to your learning using DENTIFY?; and (ii) In which exercise using DENTIFY did you find the use of the virtual mirror most helpful?

The study was conducted in three different experimentation sessions at different points in time. In each session, the student performed four tasks: (I) Black's Class I cavity on an isolated virtual tooth (left lower first molar) in the simulator (C1); (II) Black's Class II occluso-distal cavity on an isolated virtual tooth (left lower first molar) in the simulator (C1I); (III) Black's Class I cavity on a virtual tooth (left lower first molar) in arch, in the simulator (C2); (IV) Black's Class II occlusal-distal cavity on a virtual tooth (left lower first molar) in arch, in the simulator (C2I).

The free trial period was no longer than 5 minutes per user and only ran for the first test session.

Hygiene and safety. Physical contact is required to use the simulator. In the post COVID-19 pandemic period, its use by multiple students required personal protection measures to ensure hygiene and biosafety conditions, namely the use of a KN-95 mask, disposable or autoclavable cap and thorough disinfection between participants.

Ethics approval. The study was approved by the Ethics Committee of the Egas Moniz - Cooperativa de Ensino Superior, CRL, on April 28, 2022.

All methods were performed in accordance with the relevant guidelines and regulations.

Data analysis. The collected data were statistically analyzed by using descriptive and inferential methodologies, through IBM's SPSS Statistics v.28 software. A 5% significance level was set in all inferential analyzes.

Results

The participants' performance results (drill time), as a function of the experimentation sessions are displayed on Table 1. As expected, drill time decreased steadily for all tasks with increasing prototype use. However, the decrease was not statistically significant for task C1 ($p = 0.071$).

The performance results, recorded at experiment session S3, as a function of the participants characteristics and previous experience are displayed in Table 2. Overall, a higher performance is identified for participants with the following characteristics: female, non-gamer, no previous VR experience and with over 2 semesters of previous experience of working on phantom models. Significant differences are notably most present on task C1.

Task	S1	S2	S3	p*
C1	104.9 (27.0)	91.1 (28.9)	88.2 (33.3)	0.071
C1I	170.1 a (56.4)	102.5 b (34.6)	101.2 b (36.0)	<**0.001**
C2	146.9 a (58.5)	136.1 a (38.9)	112.4 b (40.7)	**0.005**
C2I	170.1 a (41.7)	140.1 b (48.2)	136.6 b (42.4)	<**0.001**

Table 1. Drill time (s) (presented as mean standard deviation) for the considered tasks, as a function of the consecutive experiment sessions (S1–S3). *RM ANOVA. statistically significant differences ($p < 0.05$) are denoted in bold. Different letters indicate significantly different means.

		n (%)	C1	C1I	C2	C2I
Gender	Female	14 (70)	81.9 (30.1)	92.9 (31.2)	103.3 (34.6)	**118.9 (36.2)**
	Male	6 (30)	103.1 (38.4)	120.5 (41.9)	133.7 (49.2)	**161.3 (43.6)**
Previous experience in performing dental cavities on phantom models (no. semesters)	2	15 (75)	**97.7 (32.5)**	101.7 (33.5)	117.4 (42.1)	139.4 (41.6)
	>2	5 (25)	**59.7 (14.5)**	99.8 (47.2)	97.4 (36.2)	108.2 39.7 ()
Previous experience with plastic tooth models (no. of dental cavities)	15-Oct	5 (25)	83.0 (35.5)	98.7 (11.7)	116.4 (51.7)	127.2 (35.2)
	15–20	5 (25)	78.5 (32.2)	99.7 (46.8)	99.9 (13.5)	127.5 (34.1)
	20-25	5 (25)	95.4 (45.8)	106.6 (55.3)	102.9 (45.5)	146.4 (74.4)
	>25	5 (25)	96.1 (24.0)	99.9 (27.0)	130.6 (47.0)	125.3 (15.0)
Previous experience with VR	Yes	4 (20)	**115.9 (42.1)**	124.1 (54.1)	123.4 (53.1)	156.7 (61.4)
	No	16 (80)	**81.3 (28.2)**	95.5 (29.7)	109.7 (38.7)	125.3 (36.2)
Gamer	Yes	5 (25)	**110.9 (38.4)**	109.9 (53.2)	95.7 (29.2)	146.8 (57.0)
	No	15 (75)	**80.7 (28.9)**	98.3 (30.3)	118.0 (43.3)	126.5 (37.4)

Table 2. Drill time (s) (presented as mean standard deviation), at experiment session S3, for the considered tasks vs. participants characteristics/previous experience. *Comparisons by Student's t-test and ANOVA (for previous experience with plastic tooth models). Significantly different means ($p < 0.05$) are denoted in bold.

The user self-assessment was evaluated by the answers to eight questions (SAQ1–SAQ8), based on a 1–5 Likert-scale. Results are presented in Table 3.

The correlation between the participants performance (drill time), for the four tasks, and user self-assessment evaluation are presented in Table 3. It is worth mentioning the statistically significant positive correlation between (SAQ4) and a higher performance for task C2 (rho = 0.540, p = 0.014).

The correlation between the answers to the user self-assessment questions are presented in Table 4. Several significant positive correlations are identified, namely between answers to SAQ1 and SAQ2 (rho = 0.480, p = 0.032), SAQ3 (rho = 0.567, p = 0.009) and SAQ7 (rho = 0.508, p = 0.022). Additionally, the answers to SAQ2 are also significantly positively correlated with SAQ3 (rho = 0.478, p = 0.033) and SAQ6 (rho = 0.488, p = 0.029).

Discussion

The transition from pre-clinical teaching to clinical teaching in Dentistry is a unique moment in the student's life due to the vast array of technical and personal difficulties that the student must overcome. It is a challenging phase that can be considered one of the most critical moments in the construction of a professional identity, both technically and personally. The act of dentistry, in OD specifically, requires a millimetric tactile sensitivity and manual dexterity that allows for the removal of diseased tissue without damaging healthy tissue, under risk of iatrogenically damaging delicate healthy dental tissues. One of the main prerogatives of pre-clinical training is to reduce the transitional shock between simulated and real models. Simulated models should therefore be as close as possible to the clinical setting in order to minimize this transition. The authors consider that models based on and/or obtained from real tissues tend to reduce this discrepancy. The closeness between simulation and reality is one of the possibilities conferred by VR and haptic technology, both for the preparation of the medical act itself, and just as importantly, for teaching. Allowing objective assessments; increasing the repetition and number of training hours; increasing the degree of realism of pre-clinical scenarios; making the preclinical student aware of the risks of medical error and iatrogenesis; these are all dimensions added to teaching with the use of these technologies, possibly placing the student further along the learning curve. However, putting these simulator-embedded strategies to use in the teaching of operative dentistry, by itself, is not enough. Although these scenarios may be graphically irreproachable, they should be equipped with concrete measures of immediate evaluation and compared over time. Breaking down evaluation into objective parameters allows for the dissection of the student's self-criticism on the different points that constitute a clinical protocol, and therefore their awareness of its limitations and iatrogenic risk factors.

Studies[27] have demonstrated that head-mounted displays can have an effect on user performance during task execution and visual discomfort. Head-Mounted Displays' discomfort has been evaluated through Simulator

User self-assessment questions (SAQ)	Median (IQR) *	Min.-Max.	C1	C1I	C2	C2I
SAQ1—did using the simulator contribute to improving conventional OD teaching?	4 (1)	3–5	0.177	0.139	0.353	0.282
SAQ2—do you think using the simulator enhanced your interest in learning OD?	4 (2)	3–5	0.195	0.132	0.139	0.378
SAQ3—would you like to have more simulator hours?	4 (1)	2–5	− 0.008	0.017	0.000	− 0.158
SAQ4—did using DENTIFY allowed you to have a better perception on the manual force to apply?	4 (2)	2–5	0.375	− 0.046	**0.540**	0.385
SAQ5—did using the simulator contribute to improving your 3D perception of dental cavities?	5 (1)	3–5	− 0.383	0.155	− 0.016	− 0.021
SAQ6—do you consider that using DENTIFY allowed you a more independent preclinical training?	4 (1)	2–5	− 0.009	0.002	− 0.001	0.154
SAQ7—do you consider that a more prolonged exposure to DENTIFY could contribute to improving your manual dexterity?	4 (1)	1–5	− 0.035	− 0.188	0.172	0.155
SAQ8—do you consider that the prolonged contact warnings were beneficial for your personal perception of the overheating risks when performing a dental cavity?	5 (0)	3–5	− 0.029	− 0.182	0.237	0.094

Table 3. User self-assessment evaluation. * *IQR* interquartile range. Correlation between performance (drill time (s)) and answers to the user self-assessment questions (SAQ). Statistically significant correlations ($p < 0.05$) are denoted in bold.

	SAQ1	SAQ2	SAQ3	SAQ4	SAQ5	SAQ6	SAQ7	SAQ8
SAQ1	–	**0.480**	**0.567**	0.232	0.269	0.226	**0.508**	0.316
SAQ2	–	–	**0.478**	0.012	0.332	**0.488**	0.390	0.259
SAQ3	–	–	–	− 0.398	0.281	0.353	0.322	0.179
SAQ4	-	–	–	–	− 0.017	− 0.235	0.051	0.343
SAQ5	–	–	–	–	–	0.185	0.128	0.378
SAQ6	–	–	–	–	–	–	0.629	0.419
SAQ7	–	–	–	–	–	–	–	0.352
SAQ8	–	–	–	–	–	–	–	–

Table 4. Correlation between the answers to the user self-assessment questions (SAQ). *Statistically significant correlations ($p < 0.05$) are denoted in bold.

Sickness Questionnaires (SSQT), oculomotor scores of Simulator Sickness Questionnaires (SSQO), and Visual Strain Questionnaires scores (VSQ)[27]. Furthermore, visually induced motion sickness (VIMS) or simulation sickness, are not to be underestimated and can be considered as an obstacle to the massification of these technologies[28]. Head-Mounted Displays manufacturers must not underestimate these factors and be aware of them during design product and commercialization. Despite the possibility of current HMD devices inducing simulator sickness, none of the participants of our study reported any situation of cyber sickness (e.g., headaches, visual discomfort, etc).

The exact timing for introducing simulators with VR and haptic pens into the preclinical student's learning path in OD has been discussed and promising results have been reported when they are exposed to the simulators prior to simulation on plastic models[29], as it amounts to a complementary strategy to traditional teaching methods[30].

Unlike other dental virtual reality simulators used in OD, DENTIFY includes the simulation of caries removal on more than one tooth (depending on the degree of difficulty established for the given exercise), isolated or in its position in the dental arch, bimanual handling, and indirect zoomable vision using a virtual dental mirror. It already includes a multisensory stimulation by incorporating visual, tactile, and auditory stimuli in the VR environment. Furthermore, it allows the learner real-time feedback and evaluates task performance on a set of predefined metrics both per user and per use (Fig. 5). This version consists of the consistent natural evolution of the previously presented simulator[25].

One of the parameters used to evaluate student performance was the progression of task completion time from S1 to S3. There was a general reduction in the time taken to perform all cavities, by all students, both in single tooth and in arches, and in both types of dental cavities (Black's classes I and II), from the first to the third session, although this was not statistically significant regarding C1. The overall improvement may be attributed to the fact that the students got used to the simulator and, therefore, had greater dexterity in performing dental cavities in a virtual environment as a result of frequent use. The repetition of the task allowed all students to show similar improvements in task completion times. Interestingly, the reduction in execution time between the first and third sessions was more noticeably observed in female students in all tasks performed, especially for C2I. It would be expected that students with more experience in performing cavities on plastic models would show shorter task completion times in the simulator. This relationship was observed. Students with less training time with plastic models showed longer execution times in all tasks, compared to the students with more than 2 semesters of experience in performing cavities in phantom heads, in the preclinical teaching context.

It is relevant and interesting to report that the students that classified themselves as gamers showed no significant reduction in execution times compared to the non-gamers. Interestingly, non-gamer students, in the third testing session, showed significantly better results in the Class I cavity situations in virtual isolated tooth (C1). This result allows us to assume that previous experience with computerized challenges and goal achievement scenarios, as well as frequency and time of experience with computer games, proved to be non-fundamental to the acquisition of manual dexterity in the simulator; in other words, users with no previous gaming experience could expect a performance progression similar to that of gamers. Importantly, and similarly, students without virtual reality experience showed superior drilling times in all tasks performed, in the third testing session. However, no significant differences were detected in the improvement of task execution times between students with prior VR experience relative to students with no prior VR experience for C1I, C2 and C2I tasks. This difference was only found to be statistically significant for task C1.

When comparing gamers vs. non-gamers, and experience with VR vs. no VR experience, the authors consider it possible to attribute these results to the interface design and the specific nature of the task. On the one hand, regarding the virtual environment, the scenarios presented are of such easy accessibility and of intuitive interaction that it allowed non-gamers/non-VR experienced students to encounter little difficulty when navigating and interacting in the virtual scenario, and even present faster task execution. On the other hand, if inexperience in gaming/VR is not a conditioning factor in the results obtained in the simulator, we can infer that it is expected that a gamer/user of VR with no previous education in OD will not show better results than a pre-clinical dentistry student with no gamer and inexperience in VR. The theoretical training process in OD appears to be a limiting factor in simulator performance (not gaming/previous VR experience, per se).

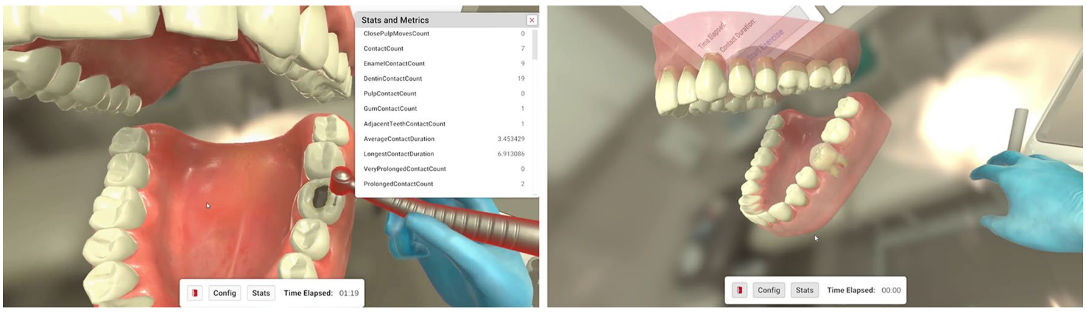

Figure 5. Over the duration of the exercise an array of metrics is collected and saved for analysis. These metrics can be monitored in real time by an examiner on the computer screen. The gums along with every layer of the tooth tissue can be set to translucent or invisible allowing users to easily view inner structures like the dentine and pulp that would otherwise always be obscured.

Regarding the use of phantom heads as a pre-clinical teaching method in OD, the users were very clear in pointing out their pedagogical usefulness. However, they also pointed out negative parameters of their use, such as matters of cost; difference in texture between phantom and natural teeth; absence of information about pressure and prolonged (potentially iatrogenic) contacts between drill and model; absence of visual limits of the prepared cavities; absence of notion of overheating of drills; absence of indirect vision. Additionally, 100% of the students mentioned that procedure evaluation in plastic models could be a result of subjective appreciation. On a grading 1–5 Likert-scale, the students considered, with statistical significance, that exposure to the simulator: contributes to improving traditional teaching; has increased their interest in OD; improves manual perception of the force to be applied on the turbine; and decisively promotes perception of dental cavities' spatial dimensions. The students also mentioned that they would like to have more hours of exposure to the simulator after the 3rd test session. Users additionally considered that simulator training contributes to more independent learning, and that prolonged exposure to the DENTIFY virtual environment may further increase their manual dexterity despite the subjective nature of tactile sensitivity.

It is also relevant to report that 100% of the students pointed out the warnings for prolonged and very prolonged contact as strongly contributing to improving their self-perception of iatrogenic risk during the virtual cavity performance.

Finally, regarding the different exercises performed, 100% of the students considered that the performance of Black's Class II cavities with the virtual tooth in its position in the arch was the most relevant learning exercise in the simulator, and the exercise during which indirect view of the virtual mirror proved to be most useful. One can infer that the closer simulated scenarios approach to real scenarios, the more usefulness can be attributed to the training strategy.

Regarding guided interviews, 100% of the students responded that evaluation using conventional OD teaching methods may be subjective, i.e., that there can be discrepancies when different teachers evaluate the same task performed by the same student. In this context, they reported to have felt more objectivity using DENTIFY due to the embedded metrics on the simulator. The results of this study support the concepts guiding repetitive and deliberate practice, and the value of self-assessment in achieving better performance on the same task.

Although this study concluded the usefulness of DENTIFY as a VR and haptic pen simulator regarding student performance and assessment, it was conducted in a few weeks. To further assess the pedagogical advantages that simulator immersion can produce, one should consider comparing evaluation scores of both simulator-exposed and non exposed students. Long term studies should reinforce the utility of VR and haptic technology simulation in OD learning.

Despite cost limitations inherent to the use of these technologies, the authors consider that there is a real and present opportunity to universalize their application to teaching, promoting a healthy technological dispute that will, inevitably, not only produce increasingly realistic simulators, but also reduce the cost of these simulators, thus enabling their eventual acquisition for home use, which, in turn, endows teaching with both greater independence and greater frequency of repetition. VR and haptic technology should be introduced globally and gradually and in a standardized manner in the teaching of operative dentistry.

Conclusions

This study concluded that the DENTIFY simulator provides pre-clinical students with pedagogical tools that may reduce the difficulty of transitioning to the clinical reality of operative dentistry, while honoring the goal of improving student performance, reducing morbidity and increasing predictability.

The simulators with VR and haptic pens for teaching in OD should be designed as a consistent and gradual teaching strategy, allowing multiplicity of simulated scenarios, bimanual manipulation, and the possibility of real-time feedback to allow for the student's immediate self-assessment. Additionally, they should create performance reports per student to ensure self-perception of their evolution over longer periods of learning time.

Future work

The use of VR and haptic devices in preclinical learning, not only in OD but also in other fields of Dental Medicine has demonstrated promising results since it has shown to accelerate the acquisition of the motor skills needed in Dentistry. Virtual artificial models of teeth and cavity types have been applied with promising results in a global strategy to decrease the difficulties in the preclinical to clinical transition. The authors consider this to be a most valuable input in promoting the acquisition of manual dexterity, which is fundamental in this field. However, a few difficulties are still present in today's contemporary simulators. It is the authors' belief that increasing the degree of realism in the virtual models can, ultimately, further reduce the distance between simulated virtual models and clinical reality. For instance, as we presented in DENTIFY, the use of real teeth for constructing our virtual environment. We intend to place futures focus on including real clinical cases by use of scanning into our simulator. Furthermore, additional hours of work must be put on improving the deformation provoked by virtual drills on virtual models, in order to approach a raw clinical environment. In this context, the preclinical VR dental student must be confronted with a greater number of clinical situations and so more scenarios must be added to simulators, without disregarding the degree of difficulty of these such tasks. a crescent degree of difficulty , which allows for sustained learning, should be considered. Self assessment and self criticism can become powerful learning tools when they are the result of objective performance evaluation through universally accepted metrics. Further consensus is necessary in order to transfer accurate evaluation criteria into dental learning simulators.

VR simulators can be a promising strategy in learning OD. However, their current cost demands a huge financial investment. This technology can only become a real massive presence in dental schools worldwide when production and commercialization prices decrease.

The presented results were very encouraging for the subsequent development of DENTIFY. In addition, the authors hope that these results may serve to stimulate research and other researchers for the purposes of introducing progressively better and more realistic models in dental education. Although momentaneously limited to OD, our main objective is to convert it into a multidisciplinary simulator in Dental teaching, both in undergraduate and postgraduate contextes. Once we've finished the Operative Dentistry simulator, we intend to bring other departments closer and involve them in the construction of a full DENTIFY concept. Our domestic implementation plan includes gradually immersing our dental students in the DENTIFY ecosystem by adding different teaching scenarios. DENTIFY is, ultimately, a pedagogically-driven concept with the objective of bringing these most promising technologies in service of our student's difficulties. We wish for our students to be able to include number of simulation hours and virtual tasks performed (similarly to what actually happens in Aviation), hoping that these enhance their dental skills and, simultaneously, give them a competitive edge when entering the work market.

Our participants were in good physical health and had no relevant issues that could affect the use of VR headsets. Pre-existing physical impairments can be considered to have influence on user performance and, subsequently, experimental results. These must be taken into consideration for these technologies to become generally accessible in dental schools. Visual impairments are normally corrected by spectacles or contact lenses (it may be interesting to explore whether these corrective measures impact performance) and the probability of undiagnosed visual diseases is seldom. This variable should be addressed in future tests (Supplementary Information S1).

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Author contributions
All persons who meet authorship criteria are listed as authors, and all authors certify that they have participated sufficiently in the work to take public responsibility for the content, including participation in the concept, design, analysis, writing, or revision of the manuscript. Furthermore, each author certifies that this material or similar material has not been and will not be submitted to or published in any other publication before its appearance in Scientific Reports. All authors reviewed the manuscript.

Competing interests
The authors declare no competing interests.

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CHAPTER 6

GENERAL DISCUSSION, CONCLUDING REMARKS AND FUTURE DIRECTIONS

GENERAL DISCUSSION

The encouraging results obtained from the aforementioned published studies (1, 2, 3) allow us to conclude that teaching tools developed using HVRS demonstrate potential for pre- and post-graduation pre-clinical teaching in Dentistry, namely in the areas of Dental Implantology and Operative Dentistry. In tests with users with different degrees of experience and age, both in IMMPLANT (the oral Implantology component of DENTIFY), and the simulator's Operative Dentistry module (DENTIFY OD), the interaction and visualization methods, as well as the multisensory immersion allowed by the simulator, were considered essential factors to awaken curiosity and increase the number of repetitions and total simulation time. It is undeniable that, to date, the prototypes present different degrees of differentiation and offer different interaction possibilities with the virtual models, which requires an individual approach to the discussion of the results and makes it impossible to establish an absolute parallelism between both. Regardless, the NASA-TLX test results, designed to study the subjective workload felt by the users while performing the tasks in both modules, were very encouraging. This questionnaire (consisting of 6 questions focused on mental and physical effort; effort on task completion time; performance; and frustration levels) revealed that, in both, the simulator approach encompasses a low rate for the total workload dimension. There is a slight difference in experienced workload rate relative to the Dentistry module, which may be attributable to 2 factors: 1) that the tests were conducted in the post-pandemic period of COVID-19, whereby the use of KN-95 masks during task performance, with their nasal support located immediately below the headsets, contributed to headset fogging and hindered focus; and 2) that the Operative Dentistry module includes a haptic pen, which involves a greater number of commands and their manipulation is more complex. However, despite this slight discrepancy, the results indicate that performing tasks in the simulators was not considered difficult, regardless of the users' previous experience with virtual reality. This shows that, in the future, solutions must entail fewer operations commands and the existence of a physical support, which is, essentially, dependent on the improvement of hardware. This will allow for further expanded VR scenarios and user interface. It is pertinent to highlight that, apart from the simulator's ease of manipulation as indicated by the users, it also allows for more comprehensive spatial perception of the virtual models. Additionally, as verified with version 2.0 of the DENTIFY Dentistry module, in which 3rd year volunteer students of the IUEM Dental Medicine Integrated Master's Degree were submitted to three test sessions with the simulator, task execution speed was gradually lower from the 1st to the 3rd session, which indicates that repetition facilitates immersion and that, in this context, workload decreases with the increase in number of sessions. This was not observed with IMMPLANT due to that particular study's design, but it is not unreasonable to think that similar results could be obtained with a greater number of simulation hours.

System usability was tested in both IMMPLANT and the DENTIFY OD module by trained dentists, within the scope of co-design. In both cases, the System Usability Scale (SUS) questionnaire was applied, composed by 10 questions classified on the Lickert scale with the objective of measuring self-perceived usability of an interactive system. For this purpose, the average was considered to be 68 points, with 83.91 for IMMPLANT and 77.50 for DENTIFY's Operative Dentistry module, showing good usability and high learnability (they are easy-to-learn systems). The ease of use associated with rapid assimilation of the simulator's manipulation confer high pedagogical content to DENTIFY. Once again, the slightly lower usability value of the Operative Dentistry component can be attributed to the greater number of commands, multiple menus and increased physical and virtual buttons with which it is necessary to interact in order to perform the predefined tasks. The SUS values were obtained in the users' first and only contact with the simulators and these results are encouraging for the application of this technology since repetition tends to increase system usability. Even regarding IMMPLANT, participant 4 mentioned that the simulator "complements conventional practice by allowing several repetitions and recurrent practice".

Regarding SUS and NASA-TLX, IMMPLANT results are indicators on a tool that is intended for teaching and, even in guided interviews, more experienced users reported feeling confident in using IMMPLANT as it provides a sense of control, and even admitted to adopting this system in their daily practice or as a pedagogical teaching tool. Despite their lack of familiarity with VR, users were able to quickly identify prominent anatomical structures (e.g. virtual nerve position, bone, bone loss), and considered its visualization and spatial distribution to complement conventional WIMP interfaces. For future evaluation of IMMPLANT, we find it necessary to perform a comparative study with existing Implantology software in order to measure user performance.

Regarding the OD DENTIFY module, and assuming that it is intended to be a student-learning-driven project centered on student self-assessment, I consider that the first test session with senior users, Operative Dentistry professors, in the scope of the strategic co-design phase, was absolutely essential to introduce changes from version 1 to version 2. These changes produced simulator improvements that not only make it more user-friendly, but also objectivize the fundamental metrics for self-assessment. Therefore (and assuming that this project is in evolutionary metamorphosis), in addition to the aforementioned NASA-TLX and SUS results, the guided interviews with these users, from which data on user experience was collected, concluded the following: all users felt different degrees of resistance to progression in different virtual dental tissues, despite the tactile sensation subjectivity; the existence of virtual patient experience in the preclinical learning phase can mitigate the stress inherent to the transition from preclinical to clinical; there is a need to include virtual opposing dental arches; there is a need to include exercises with increasing degrees of difficulty corresponding to different levels of the learning curve; and that the simulator incorporates the pedagogical and educational requirements necessary for manual dexterity skill acquisition. Among the software and hardware changes made to the prototype, we emphasise: the inclusion of objective metrics for user (student) evaluation in version 2; the existence of virtual opponent dental arches; the existence of different types of virtual burs; the inclusion of zoomable indirect vision; the inclusion of exercises with virtual teeth, either alone or in their position in the virtual dental arches; and the physical change of the haptic pen to a 3D printed plastic turbine attached to the haptic device though in a natural position, closer to reality. These changes had a significant impact on the in student test results, this simulator’s target audience.

I consider the student test results using version 2 of Dentify Operative Dentistry the most important, insofar as they reflect the simulator’s most advanced point of development to date, applied on the target audience for which it was developed. Truly, they reflect DENTIFY Operative Dentistry's creative and constructive process. The students adhered well to the experience with the simulator. The expected reduction in execution times between the first and third test session was accompanied by the statistically relevant user opinion that simulator exposure is a beneficial pedagogical contribution to Operative Dentistry learning; increased interest in using these technologies; improvement in the perception of the physical force to be applied during task execution; promoted greater spatial perception; contributed to more independent learning and less subjective evaluation. Overall, users considered that increasing simulator time effectively improves their manual dexterity. The most important results were the following: it would be expected that students with more experience in making cavities in plastic models would have better performance results, which was not verified; additionally, there were no performance differences between students who were gamers and non-gamers, nor between students with and without previous VR experience. These findings allow us to infer that the simulator is familiar/natural and easy to handle, and that the limiting factor in task performance is not previous exposure to computer stimuli but rather theoretical training in operative Dentistry.

A constant and unchanging factor of both Dentistry and Implantology modules was the possibility of self-assessment. On the one hand, in IMMPLANT, it was possible to verify the immediate correction of virtual implant placement in a position the user considered wrong; each time they were not satisfied with the result, the user would remove the virtual implant and relocate it to a different depth and/or inclination. On the other hand, regarding DENTIFY Operative Dentistry, students were able to foresee the risk of (virtual) iatrogenesis by having visual information available pertaining to the virtual tissues on which they were working; by being aware of their task execution times and their evolution from session to session; but, above all, by being informed of prolonged or very prolonged contact times between the virtual drill and the virtual dental tissues. Parameters like these effectively allow for continuous intraoperative evaluation of a virtual task; and, once incorporated in the preclinical student's mindset, these can potentially be transferred to the clinical to reality with patients. In addition to immediate intraoperative evaluation, successive use of the HVRS should allow the student to track his/her evolutionary curve and become aware of how evaluation patterns change over time of simulator use. The prolonged use of DENTIFY should be objectively and numerically translated into performance reports that take into account clear and fully established evaluation criteria according to the specificity of each curricular unit it simulates. IMMPLANT and DENTIFY Operative Dentistry have revealed, through results obtained, that the limiting factor in the evolution of these simulators is not previous contact with the technology but may be the existence of previous research within the subject being tested.

FUTURE DIRECTIONS

The results of HVRS studies in Dentistry seem to be consensual on the manual dexterity improvement they produced in their users, and the capacity for student self-criticism enabled by real-time evaluation. There is, however, much to be done to improve these simulators.

The presented "DENTIFY" modules are undeniably at different programming stages. On the one hand, "IMMPLANT" ("DENTIFY Implantology") will have to include some of the properties that DENTIFY Operative Dentistry already offers. Undeniably, it is crucial to learn where and at what angulation to place a dental implant in order to reduce intraoperative surgical risks and ensure an optimal prosthetic outcome. The spatial perception allowed by "IMMPLANT" has been well received by users but still needs further work to achieve the desired standards. Replacing the smartphone with a haptic pen that tactilely distinguishes different resistance to progression in different virtual bone types; the inclusion of performance metrics; the inclusion of local reference anatomical landmarks (especially those that may cause fatalities), anatomical references (because surgical anatomy is topographical and not descriptive); the inclusion of a database containing different implant types and objective performance measurement reports. These improvements should undoubtedly be considered in future versions. This work is currently in progress.

Regarding DENTIFY Operative Dentistry, we will try to optimise the existence of training and academic evaluation modes, both with different exercises corresponding to increasing degrees of difficulty. To this end, we will have to clarify the goal metrics for each of the modes. The introduction of emergency scenarios, increasing the number of virtual clinical cases, and adding a resting point for the support finger are also planned. Our participants were physically healthy and had no relevant problems that could affect the use of the VR headset. Pre-existing physical impairments can be considered to influence the user's performance and subsequently the experimental results. These should be taken into consideration if these technologies are to become generally accessible in dental schools. This variable should be addressed in future tests.

Generally speaking, the use of VR and haptic devices in preclinical learning, not only in Dental Medicine but also other fields of Dental Medicine, has yielded promising results and, in Dental Medicine training, it has shown to accelerate the acquisition of the necessary motor skills. Virtual artificial models of teeth and cavity types have been applied with promising results in a global strategy to decrease difficulties in the preclinical to clinical transition. The development of DENTIFY is grounded on the improvement of preclinical pre- and post-graduate education by reducing the gap between simulation and real clinical situations. In this context, I consider it essential that the virtual models used in the simulators are obtained from real clinical data. We intend to place futures focus on including real clinical cases into our simulator.

HVRS technology will undeniably have to become more affordable if it is to become an effectively globalised alternative in conventional pre-clinical dental training. Technologies should put positive pressure on educational institutions to improve the quality of the professionals they train by increasing predictability and reducing the morbidity of clinical acts performed in vivo. This pressure will be felt not only in the financial efforts by educational institutions to acquire this equipment but will also require an adaptive effort from the teachers. The adoption of HVRS will presumably encounter obstacles in its massification and dissemination process on a worldwide scale due to the need to generate global consensus on the uniformity of evaluation criteria. I consider their globalisation an inevitability. Efforts should be made to make HVRS real pedagogical tools applicable in dental schools because, in fact, until holographic technology is developed to the point that it can be manipulated without VR headsets, allowing for an individualised reconstruction that can be deformed and viewed by multiple users on the same observation plane, HVRS is the most advanced alternative to virtual simulation in health education and, more specifically, in Dentistry.

CHAPTER 7

BIBLIOGRAPHIC REFERENCES

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C1. General Introduction

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CHAPTER 8

ANNEXES

ANNEXES

Annex 1. Authorization to include Scientific Article

"An immersive educational tool for dental implant placement: A study on user acceptance"

Gmail   Mariana Morgado <marianamendesmorgado@gmail.com>

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Pedro Rodrigues

Annex 2. Authorization to include Scientific Article

“Usability, acceptance, and educational usefulness study of a new haptic operative dentistry virtual reality simulator”

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Date: Monday, June 26, 2023 02:32 PM GMT

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The article name is: Usability, acceptance, and educational usefulness study of a new haptic operative dentistry virtual reality simulator. The DOI is: https://www.sciencedirect.com/science/article/abs/pii/S0169260722002139?via%3Dihub

Beste regards

--

Pedro Rodrigues

Annex 3. Authorization to include Scientific Article

"Preclinical dental students self-assessment of an improved operative dentistry virtual reality simulator with haptic feedback"

Gmail

Mariana Morgado <marianamendesmorgado@gmail.com>

Fwd: Authorization to include my paper on my PhD Thesis
1 message

Pedro Rodrigues <pmsilvarodrigues@gmail.com>
To: Mariana Morgado <marianamendesmorgado@gmail.com>

Wed, Jun 28, 2023 at 4:46 PM

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From: Pedro Rodrigues <pmsilvarodrigues@gmail.com>
Sent: 26 June 2023 15:36
To: Journalpermissions <Journalpermissions@springernature.com>
Subject: Authorization to include my paper on my PhD Thesis

[External - Use Caution]

Dear Sim/Madam

I would like to include the work I published as an author in my POhD Theses. To do so, I need your formal authorization.

The article name is: Preclinical dental students self-assessment of an improved operative dentistry virtual reality simulator with haptic feedback.

The DOI is: https://doi.org/10.1038/s41598-023-29537-5

Best regards

--

Pedro Rodrigues

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Pedro Rodrigues

Annex 4. Egas Moniz Ethics Committee Approval | Internal Process nº 1098

Comissão de Ética EGAS MONIZ

Proc. Interno nº 1098

Ex.mo Senhor
Pedro Rodrigues

Monte de Caparica, 28 de abril de 2022.

Ex.mo Senhor,

Em resposta ao Pedido de Parecer que submeteu à apreciação da Comissão de Ética da Egas Moniz, com o tema denominado **"Dentify – Realidade Virtual e interface háptica no Ensino PréClinico em Dentisteria Operatória – Testes com utilizadores"**, foi aprovado por unanimidade.

A Presidente da Comissão de Ética da Egas Moniz

Profª. Doutora Maria Fernanda de Mesquita

EGAS MONIZ – COOPERATIVA DE ENSINO SUPERIOR, CRL
Campus Universitário – Quinta da Granja – Monte de Caparica
2829-511 Caparica

Annex 5. Egas Moniz Ethics Committee Approval | Internal Process nº 1184

EGAS MONIZ SCHOOL of HEALTH & SCIENCE

Comissão de Ética EGAS MONIZ

Proc. Interno nº 1184

Ex.mo Senhor
Pedro Rodrigues

Monte de Caparica, 26 de janeiro de 2023

Ex.mo Senhor,

Em resposta ao Pedido de Parecer que submeteu à apreciação da Comissão de Ética da Egas Moniz, com o tema denominado: **"DENTIFY – Realidade Virtual e Háptica no Ensino em Implantologia Dentária e Dentisteria Operatória – uma abordagem à simulação multimodal : Testes com utilizadores"**, foi aprovado.

A Presidente da Comissão de Ética da Egas Moniz

Professora Doutora Maria Fernanda de Mesquita

EGAS MONIZ – COOPERATIVA DE ENSINO SUPERIOR, CRL
Campus Universitário – Quinta da Granja – Monte de Caparica
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