Development and Assessment of a Three-Dimensional Tooth Morphology Quiz for Dental Students

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ABSTRACT

Tooth morphology has a pivotal role in the dental curriculum and provides one of the important foundations of clinical practice. To supplement tooth morphology teaching a 3D quiz application (app) was developed. The 3D resource enables students to study tooth morphology actively by selecting teeth from an interactive quiz, modify their viewpoint and level of zoom. Additionally, students are able to rotate the tooth to obtain a 3D spatial understanding of the different surfaces of the tooth. A cross-over study was designed to allow comparison of students' results after studying with the new application or traditionally with extracted / model teeth. Data show that the app provides an efficient learning tool and that students' scores improve with usage (18% increase over 3 weeks, $P < 0.001$). Data also show that student assessment scores were correlated with scores obtained while using the app but were not influenced by the teaching modality initially accessed ($r^2 = 0.175$, $P < 0.01$). Comparison of the 2016 and 2017 class performance shows that the class that had access to the app performed significantly better on their final tooth morphology assessment (68.0% ± 15.0 v. 75.3% ± 13.4, $P < 0.01$). Furthermore, students reported that the 3D application was intuitive, provided useful feedback, presented the key features of the teeth and assisted in learning tooth morphology. The 3D tooth morphology app thus provides students with a useful adjunct teaching tool for learning dental anatomy.

Keywords: dental education, anatomy education, tooth morphology, computerized assessment, 3D tooth morphology application, mental rotation tests, symbol-digit modality test, student performance

INTRODUCTION

The study of tooth anatomy and morphology are integral foundations of a dental career (Bogacki et al., 2004; Kato and Ohno, 2009; Cantin et al., 2015; de Azevedo et al., 2015). Tooth morphology is the study of the anatomy and morphology of permanent and deciduous teeth (Obrez et al., 2011), and is usually taught in the initial years of dental courses (Kilistoff et al., 2013; McHanwell, 2015). Dental surgery students, as well as dental hygienists, technicians and nurses, study detailed tooth morphology as it aids in recreating lost tooth structure for clinical work and also assists in dental laboratory work (Abu Eid et al., 2013; de Azevedo et al., 2015; Bakr et al., 2017). Furthermore, knowledge of anatomical features of the teeth also helps understanding their normal anatomy and interactions, as well as identifying developmental anomalies and pathologies (Obrez et al., 2011; Bakr et al., 2017). Although this module is usually taught in the first two years of dental courses, its application and use is in the clinical years leading to what has been referred to as 'decontextualized technique learning' (Bogacki et al., 2004; Obrez et al., 2011; de Azevedo et al., 2015; Magne, 2015). Traditional teaching methods for tooth morphology typically include lectures (Bogacki et al., 2004; Lone et al., 2018) supported by practical study sessions using extracted teeth (Mitov et al., 2010; Cantin et al., 2015; Lone et al., 2018), plastic teeth replica (Obrez et al., 2011; Lone et al., 2018), wax or chalk carving of teeth (Wallen et al., 1997; de Azevedo et al., 2015; Lone et al., 2018) and drawing 2D images of teeth (Abu Eid et al., 2013; Magne, 2015; Lone et al., 2018). While studying with extracted teeth is preferred (Cantin et al., 2015), pressures have increased the need to review this model, including the capacity to procure and retain adequate numbers of teaching specimens without decay or excessive wear, reduction in teaching hours, curricular integration as well as hygiene and ethical considerations.

The dental schools in Ireland, University College Cork (UCC) and Trinity College Dublin (TCD), both offer a five-year undergraduate bachelor degree in dental science (BDS) while UCC also offers an accelerated four-year degree for non-European graduates with a science degree. The completion of the BDS entitles graduates to register as dentists with the Dental Council of Ireland and with dental councils in countries of the European Union and in Canada. Undergraduate students gain admission to dental school after completion of a secondary level education (Lynch et al., 2006) while graduate entry to the four-year program requires a B.Sc. in a life science discipline with requirements in anatomy, physiology and biochemistry. Tooth morphology, is taught in the second year of both curriculums by using primarily, extracted teeth and plastic teeth for study and examination purposes (Lone et al., 2018).

Computer-aided learning (CAL) can be used to support traditional teaching leading to blended learning methods (Nance et al., 2009; Maggio et al., 2012). The use of CAL provides users with flexibility in learning, allowing pace control and reviewing (or repeating) the material multiple times while reducing faculty involvement (Nance et al., 2009). Furthermore, a blended learning design not only provides curricular flexibility, but also addresses differences in students' learning styles (Bogacki et al., 2004; Cantin et al., 2015).

Incorporating three-dimensional (3D) elements in anatomy teaching has been shown to favor spatial understanding and visualization of the relationship between different structures (Allen et al., 2016). Furthermore, recent advances in the utilization of 3D technology such as cone-beam computerized tomography in dental practise requires dental students and clinicians to manoeuvre and recognize 3D tooth images (Bell et al., 2003; Hajeer et al., 2004; Benavides et al., 2012). Recent studies exploring the link between the use of 3D teaching methods to improve understanding of complex anatomical systems and spatial ability have reported varied results

with some studies show a positive correlation (Nicholson et al., 2006; Estevez et al., 2010; Hoyek et al., 2014) whereas other studies report no significant correlation (Keedy et al., 2011; Vuchkova et al., 2011; Khot et al., 2013; Preece et al., 2013). The reasons for this variation maybe multifactorial with cognitive load theory playing a major role. Khot et al., 2013 conjectured that 3D learning is facilitated via a series of 2D images but increases the cognitive load and effort especially for the participants with poorer spatial ability (Khot el al., 2013). The spatial ability of dental students is a predictor of success especially in the preclinical courses (Hegarty et al., 2009) with student viewing dynamic 3D animations to improve their mental models (Douglas et al., 2014). Furthermore, spatial ability has been linked to improved understanding in anatomy (Qi et al., 2013) and oral radiology (Nilsson et al., 2011) in cohorts of dental students. Teaching neuroanatomy with 3D tools leads to significant improvement in cognitive and spatial ability for students (Estevez et al., 2010; Drapkin et al., 2015; Allen et al., 2016). Comparison of dental students with other student groups show that dental students have a visual learning preference (Murphy et al., 2004). Various visual innovative pedagogies have been explored for teaching the dental students such as second life (Phillips and Berge, 2009), 3D visualization software for oral radiology (Vuchkova et al., 2011) and 3D simulation (Curnier, 2010; Hackett and Proctor, 2016). A literature review of 3D technologies in anatomical education showed that a majority of studies reported positive outcomes but none reported negative impacts on cognitive loads of users (Hackett et al., 2016). Particularly, the development of 3D simulators coupled with augmented reality, automated feedback, and /or haptic response for surgical procedures has proven useful in skills development and consolidation while providing standardization of execution amongst students (Bakr et al., 2013, 2014; Perry et al., 2017; Roy et al., 2017; Kwon et al., 2018). Moreover, augmented reality was recently introduced

to teach dental procedures such as cavity preparation, showing favorable response from dental students (Llena et al., 2018). Recent advances in micro CT has led to development of 3D teeth models (Kato and Ohno, 2009; Mitov et al., 2010; Nagasawa et al., 2010; de Boer et al., 2013). Essentially, anatomy learning requires 3D spatial understanding applicable in everyday practice and can be developed as part of the knowledge and skills acquisition.

Three-dimensional interactive tooth morphology atlases have been shown to interest students and enhance learning (Mitov et al., 2010; Wright and Hendricson, 2010). Studies show that medical students enjoy learning with games for medical education (Kron et al., 2010; de Wit-Zuurendonk and Oei, 2011) with a majority of students preferring to play multiplayer games which aid in developing patient interaction skills (Kron et al., 2010). Del Blanco et al., (2017) showed how the use of a videogame can be effective in improving the quality of medical students' first visit to the operation theatre with a reduction in anxiety and error margin and improving behavior towards patients and staff (Del Blanco et al., 2017). Game-based e-learning is also reported to be effective in achieving higher cognitive learning outcomes and a positive motivational impact for medical students (Boeker et al., 2013). Dental students showed an improvement in academic writing skills following the use of game-based learning (El Tantawi et al., 2018) while improved student empathy and attitudes were noted for nursing students (Chen et al., 2015b) and pharmacy students (Chen et al., 2015a). While games have been used for teaching an array of topics and have been found to be effective, their clinical benefits for patient care need to be evaluated (de Wit-Zuurendonk and Oei, 2011).

The introduction of assessment elements in CAL resources have also been shown to be a useful tool (Mitov et al., 2010). Online tests or quizzes allow students to assess their knowledge and provide immediate feedback stimulating long-term retention of knowledge (Wright and

Hendricson, 2010; Baker et al., 2013). In addition, online tests or quizzes have been shown to maintain students' motivation and are valuable tools for examination preparation (Bogacki et al., 2004). Studies show that students have a preference for examination related material in this context (Jastrow and Hollinderbaumer, 2004; Jackson et al., 2011). Previous studies have also reported that, when using CAL, students prefer simplicity and accessibility as they don't want to waste time with technical issues and unnecessary delays (Mitov et al., 2010).

While modernization of dental anatomy teaching is gathering pace, the introduction of new tools must be measured against specific outcomes. It is clear that innovative teaching methods can stimulate students and maintain their interest, but they must also perform a didactic role. In the present study, a 3D tooth morphology quiz (TMQ) application was developed and assessed at University College Cork, Ireland. Using a cross-over design, the efficacy of the teaching aid was compared to the use of extracted permanent teeth. Students were assessed on their capacity to recognize individual teeth.

MATERIALS AND METHODS

Design of the Tooth Morphology Quiz app

The design of the TMQ application has previously been described (Lone et al., 2017). Briefly, a complete set of 32 adult permanent teeth, either extracted or anatomical replica, were digitized using the Renishaw Incise™ DS10 dental 3D contact surface scanner (Renishaw plc. Wotton-under-Edge , Gloucestershire, UK). Once appropriate scans of all surfaces were obtained, the teeth were reconstructed using the GOM Inspect software, version 7.5 SR2 (GOM GmbH., Braunschweig, Germany) and exported as a single (.STL) file. These files were imported to Blender, version 2.7.3 (Blender Foundation, Amsterdam, The Netherlands) and

applied with a custom texture created from images of the scanned teeth (Figure 1A). The Unreal Engine software, version 4.9.2 (Epic Games Ltd., Cary, NC) was used to create the 3D quiz environment.

Tooth Morphology Quiz environment and navigation

On entering the quiz environment, the user is prompted to insert a pre-assigned identifier (e.g. student registration number) that will enable the tracking of progress and will also facilitate automated data collection for the next phase of the study. The environment consists of a labelled Fédération Dentaire Internationale (FDI, ISO 3950) dental notation charting system and ten 3D teeth randomly selected from the 32 permanent teeth implemented in the app. The user has the option to “left click” to drag a tooth to a location on the FDI chart, or “right click” to zoom in on a tooth and rotate it in 3D view to study various aspects before submitting to the selected location on the chart (Figure 1B). On completing the quiz, the user is presented with a feedback screen, which is overlaid onto the main viewport (Figure 1C). This screen shows a small image of the teeth in the position where they were submitted on the charting grid. For this view, the coloration of the teeth has been altered to a standard diffuse red or green to denote that the submission is correct or incorrect. To the right of this image the user can select from a list of buttons corresponding to the incorrect entries. After selection, the corresponding tooth is highlighted in yellow and textual feedback based on Fehrenbach and Popowics’ identification cards (Fehrenbach and Popowics, 2016) is provided. The system's backend then creates a file in the system directory for each new user number. The date, time taken in the 3D quiz environment, score, and list of incorrect teeth are then recorded into this file. If a user returns to the tool, these

data are then stored in their respective file. This allows for monitoring of scores over time and also repetitions in incorrect answers.

Study design

This study was a randomized cross-over trial involving 50 second-year bachelor of dental surgery (BDS) and 14 first-year diploma in dental hygiene (DDH) students enrolled in a 12 week module of dental morphology, histology and embryology taught in the Department of Anatomy and Neuroscience at UCC (2017 cohort). The study and all questionnaires used were approved by the institutional Social Research Ethics Committee (log 2016-107A).

Students enter the BDS program through a direct entry route (BDS) where selection is based in secondary level education or a graduate entry route where the requirement is a third-level biological sciences degree (BDSG). Both the direct entry BDS and the DDH programs accept mature students in addition to school leavers. This course is taught in the second semester of the academic year and includes 15 hours of lectures and 12 hours of practical laboratory sessions with ~2.5 contact hours per week. It is supported by the university's web-based learning portal, which allows student access to lecture / practical laboratory notes, learning resources and announcements relating to lectures and laboratories. During the practical laboratory sessions, the students use a limited number of extracted human teeth and sets of high quality plastic replica to study dental morphological features of individual teeth. The recommended supporting textbook and atlas are *Wheeler's Dental Anatomy Physiology and Occlusion* (Nelson, 2015); and *Illustrated Dental Embryology, Histology and Anatomy* (Fehrenbach and Popowics, 2016). No

tooth morphology online resources were used in the laboratory sessions or recommended to the students.

The tooth morphology component of the module is assessed in the 9th week of term by a formative spot examination utilizing extracted human teeth where the students are asked to identify the extracted tooth and chart its notation using either the FDI or Palmer notation system. Students also sit a 1.5 hour, end-of-term examination comprising of essay and multiple choice questions.

Informed consent was obtained from the students at the start of the study and the participants completed a mental rotation test (MRT version A) and a symbol-digits modalities test (SDMT) to assess their mental aptitude at the beginning of the study. They also completed the pre-study questionnaire. Participants from each academic program were randomly assigned into two study groups which accessed the learning modalities in opposite order (Figure 2). Students in Group A first accessed the TMQ app for three weeks to study tooth morphology while students in Group B initially used extracted teeth to study. When studying with extracted teeth, the participants were provided with a set of 32 extracted teeth along with flash cards from *Illustrated Dental Embryology, Histology and Anatomy* (Fehrenbach and Popowics, 2016). The use of electronic equipment was not allowed during these sessions. At the completion of the first block of 3 weeks, the participants completed a mock examination (Mock 1, Figure 2) consisting of 20 stations where ten stations presented extracted teeth and ten stations presented digitalized teeth. At each station, the students were given 1 minute to identify the tooth and a mark was awarded for each correct answer. Following a three-week exposure to the second teaching

modality a second mock examination, similar to Mock 1, was conducted (Mock 2, Figure 2). The participants completed the post-study questionnaire at this stage. Finally, the students completed their end-of-term spot examination two weeks after the end of the study phase. This consisted of 20 stations presenting extracted teeth with a sub-question pertaining to the features of each tooth examined. The maximum score achievable was 40. For comparison purposes, this examination was identical to that of the previous academic cohort (2016 class) who were taught with the same parameters with the exception that they did not have access to the TMQ app. The demographic information pertaining to this cohort was extracted from academic records.

Questionnaire design

Pre- and post-study questionnaires were developed using Survey Monkey (SurveyMonkey, Inc., Palo Alto, CA). The questionnaires were designed by a team of two anatomists and two dentists actively involved in teaching anatomy. Likert-style statements, binomial (yes/no) questions, quantitative rating questions or open-ended questions were utilized. The pre-study questionnaire was comprised of 25 questions and collected data regarding student demographics, student learning styles, use of internet and online quizzes. The post-study questionnaire comprised 5 questions (with sub-questions) and collected data regarding students' experience using the app and studying with extracted teeth. Senior medical demonstrators in the Department of Anatomy and Neuroscience at UCC were invited to participate in a trial run for validation of the questionnaires. A focus group session was also organized with the medical demonstrators and questions were modified based on their feedback.

Mental Rotation Test

The visual spatial ability of the participants was assessed using the redrawn Vandenberg and Kuse Mental Rotation Test (MRT, version A) (Vandenberg and Kuse, 1978). This is the most commonly used version of MRT that examines the ability of participants to mentally rotate figures around a vertical axis. The test comprised 24 questions with each question showing a target figure on the left and four similar figures on the right. Of these, only two are rotated versions of the target figure. The test entails participants' capacity to mentally rotate the target figures and identify the two correct answers (rotated versions of the target figure). A score of '1' was awarded only if both choices were correct with the maximum score attained being 24. The instructions, procedures and scoring methods were identical to those reported by Peters et al., (1995). The results present the percentage of correct answers achieved by each student. The MRT-A scores were used to determine a possible correlation between visual-spatial ability and the ability to recognize extracted / digital teeth.

Symbol-Digit Modality Test

The Symbol-Digit Modality Test (SDMT) assesses the cognitive ability of individuals (Smith, 1982). A key consisting of ten geometric designs corresponding to the ten digits is provided to participants. The test involves participants converting rows of these geometric designs into the corresponding numbers in a time span of 90 seconds. A score of 1 is awarded for each correct response with a maximum attainable score of 110. The results show the percentage of correct answers achieved by each student.

Data analysis

Data were coded, anonymized and entered into Microsoft Excel 2016 spreadsheets (Microsoft Corp., Redmond, WA). Data were then exported to the Statistical Package for Social Scientists (SPSS), version 22 (IBM Corp., Armonk, NY). Where appropriate, descriptive statistics were provided (mean ± standard deviation, median, range, frequency or percentages). Mock and examination results were analyzed with different statistical tests. Student's *t*-tests were performed to analyze data of each groups' performance in various components of the mock examination (3D teeth spots and extracted teeth spots). Unpaired Student's *t*-tests were used to compare the means of the two groups (group A and group B) for scores obtained in mock examinations of 3D teeth, extracted teeth and end-of-term examinations. Unpaired Student's *t*-test was also used to compare examination results from the 2016 and 2017 cohorts. Analysis of Variance (ANOVA) was performed to compare the age, SDMT and MRT scores of group A, group B and the class of 2017.Cohen's *d* was used to estimate effect size between groups by difference in means divided by pooled standard deviation. Pearson's correlation coefficient (r) was utilized to identify linear association between spatial ability tests, mock examination scores and final examination scores of both groups. Differences with a P value less than 0.05 were deemed statistically significant. Cronbach's alpha was used to measure the internal consistency of the qualitative feedback questionnaire. Data from questions pertaining to the same subjects were grouped and analyzed together. In instances where sentences were phrased negatively, the Likert data were inverted. Answers to open-ended (qualitative) questions were tabulated, and qualitative themes were identified.

RESULTS

Demographics

Initially, 64 dental students were included in the study however, five students were missing at different stages of the study and their data were excluded from final analysis (N = 59). Demographics of the participants are outlined in Table 1. For the 2017 cohort, the average age was 22.8 ±3.7 years (age range, 18-37 years) and included 15 males and 44 females. The majority of students was from Europe (45.2%) with students from Canada, Asia and Middle East accounting for the reminder of the student cohort. Forty eight participants were dental students (34 direct entry and 14 graduate entry dental students) with 11 dental hygiene students. Twenty four participants (40.7%) had previously completed a third level education degree. The 2016 cohort consisted of 64 students, including 45 females and 19 males, with an average age of 21.5 ±3.9 (age range 17-36 years) at the time of their tooth morphology examination. Again, the majority were from European countries (68.8%) with 16 students from Canada (25%) and 2 from Singapore (6.2%). These students were not part of the TMQ study cohort, we therefore have limited information on their background but their tooth morphology examination score is used as a baseline comparison with the 2017 cohort (Table 1).

Participants' usage of electronic resources

Smartphones allowed participants easy access to the internet with students accessing internet daily for ~4.6 hours for various online activities. When participants' daily use of internet as well as device preference for access were queried, results reveal that students spend 4.6 ± 2.2 hours per day (range 1-10 h/day) on the internet on a typical weekday compared to 5.4 ± 2.7 hours per day (range 1-13 h/day) at weekends. Data gathered from pre-study questionnaire show that smartphones are the preferred device to access the internet (N = 58, 98.3%), followed by laptops (N = 51, 86.4%), tablets (N = 13, 22%) and desktop computers (N = 6, 10.2%). When

asked about their online activities, all the participants reported using social media, while 58 participants (98.3%) reported using the internet for communication (instant messaging) and education. Furthermore, 56 students (94.9%) reported using emails, followed by 44 participants (74.6%) reporting streaming movies / television. Moreover, 41 participants used the internet to retrieve information or shop online (69.5%), and finally 7 students (11%) reported accessing the internet for gaming.

Laptops were preferred over smartphones for educational purposes with students preferring to study at their homes. When device usage for educational purposes was inquired, data indicate that laptops are the device of choice, (N = 52, 88.1%) followed by smartphones (N = 20, 33.9%), tablets (N = 9, 15.3%) and desktop computers (N = 6, 10.2%). The participants were next asked to indicate their location when accessing the internet for educational purposes. Students' home were the primary reported location (N=54, 91.5%), followed by the university campus (N = 43, 72.9 %), public places including the library and cafés (N = 31, 52.5%), while commuting (N = 10, 16.9%) and a friend's house (N = 8, 13.6%).

Students' learning strategies

Students reported using varied learning pedagogies with visual support tools being the most prevalent. Participants were asked to select the methods they use when learning an academic topic. Results show that animations / videos were used by 33 students (55.9%) while 23 students (39.0%) reported learning topics by reading text / notes; 21 students (35.6%) reported the use of illustrated texts, while only 4 (6.8%) students indicated listening to audio recordings as a learning method (Figure 3A). The participants were next asked whether audio recording forms an important part of an educational video. The majority of respondents agreed or

strongly agreed (N = 46, 77.9%), 4 students disagreed with the statement (6.8%), while 9 students (15.3%) remained neutral.

A majority of participants routinely searched for supplementary online educational information especially for difficult topics and had downloaded an educational app on their mobiles. The students were asked if they find online searches useful while studying a new or difficult topic. The findings indicate that 98.3% of the participants (N=58) answered yes, while the remaining respondent reported a "don't know". When asked how frequently they perform online searches for such new or difficult topics, 24 participants (40.7%) reported doing searches systematically, while 27 (45.8%) students indicated searching frequently and 8 (13.6%) sometimes searching for new / difficult topics (Figure 3B). In order to analyze further the students' use of the internet, we asked whether they would routinely search for online supplementary teaching aids and quizzes. Thirty-four students (57.6%) answered yes while the remaining 25 answered no (42.4%) (Figure 3C). We next asked whether they had previously downloaded an educational app to their mobile devices. The majority of participants (45, 76.3%) reported having done so while 14 answered no (23.7%) (Figure 3C). When asked if they enjoy learning with games, 38 students (64.4%) answered yes while the remaining 21 students (35.6%) indicated no (Figure 3C). Furthermore, when asked if online quizzes are a useful learning tool, 49 students (83.1%) answered yes while 1 (1.7%) answered no, and 9 did not know (15.3%) (Figure 3C). Finally, when asked if they would use such online quizzes to test themselves while learning, 42 participants (71.2%) reported that they did, 10 participants (16.9%) answered no, while the remaining 7 (11.9%) said that they did not know (Figure 3C).

Students were confident when maneuvering a 3D image using both laptops and mobile phones. The participants were asked to rate their confidence at maneuvering a 3D image using a

laptop / computer and smartphone, expressed in a Likert scale where 1 = very uncomfortable and 5 = very comfortable. The majority of the participants reported being confident (very comfortable/comfortable) in maneuvering a 3D image using a laptop/computer (N = 42, 71.2%) or a smartphone (N = 47, 79.7%) (Figure 3D).

Assessment of group similarity

Both study groups displayed similar characteristics. Following acquisition of the pre-study data, the students were randomly divided in two study groups and asked to complete the SDMT and MRT-A under instruction of the first author. After removal of the incomplete data, Group A was composed of 15 BDS, 8 BDSG and 5 DDH students, while Group B comprised 20 BDS, 6 BDSG and 5 DDH students. The data indicate that there were no differences between the groups and class averages for age, SDMT and MRT-A scores (Figure 4A and Table 1). The class average age is 22.8 ± 3.7 years of age (range 18-37, median 22) while both test groups showed a similar distribution. The mean SDMT score for the class was 57.5% ± 9.4 (range 41.8-90.9%), with Group A scoring an average of 58.3% ± 9.8 and Group B averaging 56.8% ± 9.2. For the MRT-A, the class average was 42.2% ± 23.0 (range 0-83.3%) with Group A scoring an average of 43.6% ± 22.3 and Group B averaging 40.9% ± 23.8 (Figure 4A).

Access to Tooth Morphology Quiz app during the study period

The two study groups performed similarly on the TMQ app but improved with every week of usage. As mentioned above, the TMQ app compiled the number of attempts for each user as well as the score and time taken for each attempt. Data analysis shows that during their three weeks of access, there were 204 attempts by group A and 129 attempts by group B. The

average time for each attempt was 876 seconds for group A and 1247 seconds for group B (not shown). When the mean score is considered for individual weeks, results show a significant increase in performance over the course of the 3 weeks for each group (Figure 4B, $P < 0.0001$, one way ANOVA with Dunnett's post-hoc analysis). For each week of access, there are no significant differences between groups A and B, the average scores for weeks 1, 2 and 3 are similar for each group (Figure 4B).

Participants' performance on tooth morphology assessment

Participants' performance increased on the second mock assessment. Following a 3-week study period, the participants from both groups were assessed by a mock examination to identify 10 human extracted teeth and 10 digitalized teeth presented on a 3D image manipulation software (not in the TMQ app environment). Marks were only awarded if the correct full description of the tooth was provided. After the mock examination, the groups exchanged their study modalities for 3 weeks and a second mock examination was performed. Results show that the class as a whole performed significantly better on the second mock assessment (41.7% ± 17.0 v. 49.4% ± 16.9, $P < 0.05$ paired Student's *t*-test, not shown). When each element of the assessment is considered individually, the class of 2017 shows improvement in identification of both 3D digitalized and extracted teeth (Figure 4C, $P < 0.05$ and $P < 0.01$ respectively, paired Student's *t*-test). Results show no difference between the experimental groups in individual elements of the mock assessments (not shown). However, when the results of individual groups were compared between mock examinations 1 and 2, the data showed that students in group B performed better with extracted teeth on their second examination (Figure 4C, $P < 0.05$ paired Student's *t*-test, Cohen's *d* effect size = 0.30).

There were no differences between the final examination scores of the two groups but a comparison with the previous cohort showed significantly improved results. Comparison of groups' performance in the final examination was also carried out. Data revealed that both groups performed similarly well and that there were no differences between group performance, and that of the 2017 class as a whole (Figure 4D). To further investigate the potential contribution of the TMQ app to student performance, the examination score of the 2017 class was compared to that of the 2016 class who had received the identical examination and training but did not have access to the TMQ app. Analysis of the results shows that the 2017 class significantly outperformed the 2016 class (Figure 4D, $P < 0.01$, unpaired Student's *t*-test, Cohen's *d* effect size = 0.09). However, as class composition varies from year to year, we broke down both classes into their constituting groups (BDS, BDSG and DDH) and compared their performance on final examination. For both years, 2016 and 2017, data analysis revealed that while there were marginal differences between BDS, BDSG and DDH students' average scores, it did not reach statistical significance (data not shown).

Students' performance in their final examination was positively correlated to mock examination scores, SDMT scores and TMQ app scores. As participants were assessed using the MRT-A and SDMT tests at the initiation of the study, the data were analyzed using Pearson correlations to assess whether performance in final examination could be correlated with age, SDMT, MRT-A or mock examination scores. The results show that the students' performance in final examination is significantly correlated with their mock examination scores ($P < 0.05$, $P < 0.001$, Figure 5A) and their SDMT score ($P < 0.001$, Figure 5A). When the students' performance on the TMQ app quiz was considered it was found to significantly correlate with

performance on mock 2 and final assessment ($P < 0.05$ and $P < 0.01$ respectively, Figure 5B) and was just outside statistical significance for mock assessment 1 ($P = 0.054$, Figure 5B). Finally, when the various components of the results were further analyzed, some additional correlations were identified but none that was consistent across the groups or assessment modalities. Of particular note, the MRT-A performance was not correlated with higher performance on 3D digitalized tooth identification.

Finally, although both genders performed equally in SDMT test, males performed significantly better in the MRT-A test. When results were considered according to gender, data analysis revealed that males performed significantly better on the MRT-A test and the mock 1 assessment after the first phase of the study (Table 2). There were no other significant differences between the genders at the mock 2 or final examinations. In addition, both genders performed equally well on the SDMT test (Table 2).

Students' perception of the learning experience with the Tooth Morphology Quiz app

The participants found the TMQ app easy to use and an enjoyable tool to simultaneously learn and test their tooth morphology knowledge. After completion of the study, participants were asked to rate their perception of the learning experience with the TMQ app and extracted teeth using five-point Likert scales (1 = strongly disagree to 5 = strongly agree). The data were collated in 9 groups pertaining to discreet aspects of the app and learning process and the internal reliability of responses was calculated using Cronbach's alpha for each group (Table 3). Overall, the data indicate that the user's opinion was neutral with regards to the app (mean of 32 questions = 3.15 ± 1.21). Analyzing groups individually, the data show that overall, the app was easy to use (mean = 3.57 ± 1.10, group 1 in Table 3) with the reservation that the students had

some difficulty rotating the 3D representation of the teeth (mean = 2.96 ± 1.19, group 3). While the quality of the dental features on the digital teeth was mostly perceived in a positive way (mean = 3.26 ± 1.09, group 4) the TMQ app was not perceived to be as valuable as extracted teeth for learning tooth morphology (mean = 1.92 ± 1.11, group 6). This is in contrast with the data indicating that the participants enjoyed using the app (mean = 3.59 ± 1.07, group 7), found its feedback useful in learning tooth morphology (mean = 3.56 ± 1.08, group 8) and found the quiz aspect useful (mean 3.69 ± 0.92, group 9).

Participants' feedback

Participants enjoyed using the TMQ app but have suggestions for improvement. An open-ended question gathered students' feedback about the study and the app. A thematic analysis was performed on the qualitative data with the following themes identified.

360 degree rotation of the teeth

The program used to develop the app does not allow for a full 360 degree rotation of the teeth but rather a 180 degree rotation in each direction. Student feedback reported that students would prefer to view 3D teeth that could be rotated to 360 degrees.

"I wish it were possible to rotate the tooth 360 degrees. The rotation was limited which meant it was difficult to visualize the tooth in the maxillary position because I could not rotate it fully".

"The teeth should allow you to rotate fully 360 degrees, this way you can orient the tooth properly as if it was inside the oral cavity".

Feedback with 3D teeth images

Students found that the feedback provided on exit was helpful but would prefer it in a more structured way.

"It was very useful in that you were given feedback and it was relatively easy to use".

"I thought it was very helpful at the end when the results told you why a tooth was incorrect. For me, it was often due to mistaking right quadrant from left quadrant, and the results gave tips on how to rectify that".

"More condensed feedback almost in point form, the large paragraphs are daunting and frustrating to read through as it takes too long".

Rectify answer/change answer

The TMQ app did not allow students to change their answers once they had submitted a tooth to the FDI grid but the qualitative feedback demonstrates that students would like to have the option to change their answers.

"It would be nice to be able to change our answers during the quiz".

"I didn't like that once a tooth was placed I couldn't undo it".

One tooth quiz

The TMQ app randomly presented 10 teeth for the quiz. Feedback shows that the students would have preferred to be presented one tooth at a time and receive the feedback immediately after submitting their answer.

"I think I would have benefited more if the quiz asked one question at a time and we got the result and feedback right away".

Application available at home

The TMQ app is easy to install and does not require any plugins. The study design did not allow for home use of the app. However, students felt that they would benefit greatly from having this app at home

"I found it very helpful and it would be helpful to have it at home".

Positive feedback

Students found the app helpful and that it aided in learning tooth morphology. The 3D teeth provided technology-based learning into the current curriculum which the students found constructive to their learning

"I found this app helpful as we could work away ourselves without feeling under pressure completing it in front of others".

"I did find the app very helpful although I did also like identifying the extracted teeth as the size of the teeth are more realistic, I found it helpful learning with both combined".

"The reason I found the app helpful was because I found out at the end which tooth was which and why".

DISCUSSION

Similar to many universities, our institution faces challenges associated with curricular changes to its dental programs. In particular, the difficulty to attract and retain qualified staff, reductions in the number of teaching hours and the difficulty to retain good quality extracted teeth have all contributed to pressure in maintaining the quality of tooth morphology teaching.

While extracted teeth are still considered the best teaching tool (Cantin et al., 2015) and dental carving has been shown to improve students' manual dexterity (Bodi et al., 2007; de Azevedo et al., 2018), dentistry and dental education are being transformed by the introduction of new technologies including mobile phone apps (Khatoon et al., 2013) and the inclusion of social media for educational purposes (Spallek et al., 2015a; Spallek et al., 2015b). In particular, the introduction of cone-beam computerized tomography in practice has increased the need for the development of pedagogical elements dealing with the 3D representation and interpretation of anatomical and dental structures. Anatomy textbooks and atlases provide limited benefit with regards to 3D visualization of structures as they present static 2D images (Langlois et al., 2015). The visual-spatial ability to mentally manipulate a 3D structure and recognize its features is becoming increasingly important as time with appropriate anatomical models is reduced and reliance on 2D images is increased (Azer and Azer, 2016). In a recent review of available studies of 3D anatomical models, Azer and Azer (2016) failed to identify clear benefits of 3D models over traditional teaching methods using 2D representations. While some studies showed better outcomes using traditional teaching, other showed benefits using the 3D models. It must be noted however that the wide variety of study designs and the purpose of the 3D model may influence the outcomes (Azer and Azer, 2016). The present study introduced and assessed a 3D Tooth Morphology Quiz app aimed at providing a self-directed learning alternative to extracted teeth or plastic models.

The integration of quizzes with other instructional activities in healthcare education has generally received positive feedback (Adamczyk et al., 2009; Jackson et al., 2011; Khatoon et al., 2014). In the present study, the incorporation of the quiz element as the basis of the TMQ app was to provide formative assessment to the participants. This design was based on three main

drivers identified by Evans et al., (2014). The formative assessment should inform students of the gap in their learning; it should familiarize them with the expectations of the summative assessment and provide feedback that guides them in their learning. From the results, it is clear that the TMQ app has, at least in part, achieved its goal. The weekly improvement in TMQ score, the increased performance on mock and final examinations, and the feedback from the users all suggest that the TMQ app does indeed provide a formative environment that is aligned with the summative assessment of this course (Evans et al., 2014).

Following the initial collection of data, the participants were divided into two cohorts with similar BDS, BDSG and DDH student ratios, however due to incomplete data; a number of participants were excluded from the data analysis, slightly skewing the groups' composition. Data analysis showed that both groups had similar age profiles and performed equally well on both pre-study tests. While the SDMT is typically used to measure neurocognitive learning deficits, we assessed the cohort of dental students to ensure that both groups performed equally well. The class average (57.5% ± 9.4) is slightly higher than what has been previously reported for populations of post-secondary students (Sheridan et al., 2006; Kiely et al., 2014), but could be a reflection of the high grades required to enter the dental programs. While there were no differences between groups A and B in terms of SDMT performance, a correlation was observed between the SDMT score and the total achieved in the second mock (not shown) and final examinations, possibly indicating a link between SDMT score and capacity to perform in a pressurized examination setting.

Previous research has highlighted a link between MRT scores and performance in anatomy examination (Guillot et al., 2007; Hoyek et al., 2009). The average MRT-A score for the 2017 class (42.2% ± 23.0) is in line with results previously reported by Peters et al., (1995)

for student populations (45%). Male participants performed significantly better than female students in the MRT-A (Table 2), in line with previous reports (Vandenberg and Kuse, 1978; Peters et al., 1995; Guillot et al., 2007; Nazareth et al., 2013; Krüger and Suchan, 2016). Male participants also outperformed their female counterparts in both aspects of the first mock assessement, although this difference disappears in subsequent assessments. Neubauer and colleagues (2010) previously suggested that training reduces the male-female gap in 2D and 3D mental rotation tests (Neubauer et al., 2010). The increased performance observed in female participants in mock 2 and final assessments could be a reflection of such training effect or increased familiarity with the material.

In addition to the training effect discussed above, data analysis revealed that mean quiz scores as computed by the TMQ app increased after each additional week of usage, suggesting a potential learning effect. While it could be argued that it may be a reflection of students learning material in their own time as the academic term progresses, the data show that the scores for groups A and B, who had access to the app at different times in the teaching term, were similar at the same time points, suggesting incremental performance within the confines of the TMQ app. The data further support this, as performance within the TMQ app was shown to significantly correlate both with mock and final assessments scores, suggesting that the TMQ app contributes to the consolidation of knowledge. Detailed analysis of the mock assessment data showed that only group B achieved a significant improvement in performance in mock assessment 2, and this only applied to extracted teeth. This could be a reflection of the sequence of learning implemented for group B in the study design. These participants used the TMQ app for the initial three weeks followed by three weeks of study with extracted teeth. Their improved performance

could be attributed to this sequence or simply that, as they had just completed the study phase with extracted teeth, they were more familiar with the material.

The success rate was very low in both mock assessments (below the academic pass threshold of 50%), much lower than in the final assessment, suggesting that students had not fully engaged with the material and that additional study outside the laboratory setting further consolidated their learning. The 2017 class as a whole performed better on mock assessment 2 than on mock 1 (49.4% ± 16.9 v. 41.7% ± 17.0, not shown), further supporting the presence of a training effect both with the TMQ app and with the extracted teeth. The difference in final assessment between the 2016 and 2017 classes further suggests that implementation of the TMQ app helped consolidating learning of the 2017 cohort by giving the students additional time with the teaching material. While it could be argued that this may reflect changes in class composition between 2016 and 2017, data analysis revealed no significant differences in performance between the BDS, BDSG and DDH cohorts, further strengthening the contention that the TMQ app afforded the students more time with the teaching material than with current limited resource of extracted teeth, thus consolidating their knowledge. Bakr et al. (2016a), had previously reported similar performance improvement using flipped-classroom techniques where students were allocated additional time with the teaching material. As students in both groups A and B performed equally well in the first assessment, it suggests that the knowledge acquired using the 3D visualization tool in the TMQ app can be translated to extracted teeth and consolidated by the formative quizzes. This is in line with results reported by Bakr et al. (2016b) using digital cadavers for head and neck anatomy for dental students.

The participants' preference for smartphones and laptop computers for general internet access, and laptop computers as the preferred tool for educational access to internet resources is

in line with a recent study by Khatoon et al., (2014) that found similar trends and suggested that mobility may play an increasingly important role in the choice of device (Khatoon et al., 2014). The results of the study provide further support with regard to mobility as a key factor in device choice, showing that while the majority of participants access the internet from home, a significant proportion also reports accessing it from the campus or public places.

As mobility plays an increasing role in the method of study, computer applications designed to support it will also play a more important role. There are a number of tooth morphology applications available (Mowery et al., 2010; Skelton-Macedo and Nayyar, 2013; Nelson, 2015; Salajan et al., 2015; Javaid et al., 2016) but there is limited research demonstrating their pedagogical validity. It is essential for these applications to be reviewed by students and professionals and evidence-based, research generated results provided to show their validity and efficiency (Khatoon et al., 2013). Most of the apps currently available focus on both the permanent and primary teeth whereas the TMQ app focused on the permanent teeth only. While some apps required a plugin (Skelton-Macedo and Nayyar, 2013; Salajan et al., 2015) the TMQ was easily installed in the PCs and laptops and did not require any plugins. Moreover, quiz or examination are available with some applications (Mowery et al., 2010; Javaid et al., 2016), but other applications do not offer any tools to assess user learning (Skelton-Macedo and Nayyar, 2013). The TMQ app presented here is unique in that it offers dental students an opportunity to actively study tooth morphology using 3D images and test themselves using the FDI notation system. This will not only improve student understanding of tooth morphology but also facilitate and bridge the gap between basic and clinical years with students ease in using the notation systems. Repetitive teaching with feedback has been shown to be instrumental in enhanced learning of procedural skills feature recognition (Al-Rawi et al., 2015; Bosse et al., 2015;

Sennhenn-Kirchner et al., 2018). The TMQ app utilized 3D scans of the extracted teeth used in the practical sessions, thus allowing students an opportunity to visualize the 3D scans of the identical teeth and affording them an opportunity to translate and compare the knowledge acquired within the TMQ app to the extracted teeth.

While a mass of data regarding the suitability of 3D visualization systems in general and specialist medical education, very few studies have analyzed the validity of these tools in dentistry. An increasing number 3D anatomy teaching packages and virtual reality simulators with augmented reality or haptic feedback are being developed to train dental students and practitioners in specific procedures but very few have been thoroughly tested for completion of their pedagogical objectives (Perry et al., 2017; Roy et al., 2017; Kwon et al., 2018). As it is clear that the adoption of such packages will be increasing to alleviate curricular pressures, counteract staff shortages, meet regulatory demands or simply provide students with a broader learning experience, the emphasis must remain on the assessment of the suitability of the tools in the context of the dental course objectives.

Limitations of the study

The study was performed on a small number of dental students from a single institution. The study initially included 64 dental and dental hygiene students however, complete data were obtained for 59 students only (7.8% non-completion rate). This led to a disparity between groups A and B. The student cohort also had a gender imbalance reflective of the student population studied with a majority of females as compared to males.

There are numerous tooth morphology applications available to download and these could have been used by the students to study. While every effort was made to keep the two

student groups separate, we could not control for the exchange of knowledge during study time. Finally, while we standardized mock assessment 1 and mock assessment 2, it is possible that slight differences in their degree of difficulty were present.

CONCLUSIONS

The aim of the study was to develop a tooth morphology quiz app to demonstrate the 3D structure of individual teeth to assist in student learning. Furthermore, a game-based environment was used to provide the learner with formative feedback. The data indicate that the TMQ app was equivalent to extracted teeth and can be used as a supplemental tool in teaching tooth morphology. The TMQ app offers students unrestricted practice time and could be deployed in both basic and clinical years to reduce the occurrence of decontextualized learning. The study provides further support that innovative technologies can present teaching material in a novel and efficient manner to supplement traditional teaching. The success of 2D and 3D applications has paved the way for the development of virtual and augmented reality packages. Navigation of anatomical structures in a virtual environment is increasingly adopted as a supplemental tool to traditional teaching. These methods are student friendly and lead to a better experience and enhanced teaching outcomes. These strategies are as effective as traditional teaching methods while allowing the students to study at their own pace with or without repetition. It also reduces workload on the faculty while providing faculty members the opportunity for increased interaction with the students.

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LITERATURE CITED

Abu Eid R, Ewan K, Foley J, Oweis Y, Jayasinghe J. 2013. Self-directed study and carving tooth models for learning tooth morphology: Perceptions of students at the University of Aberdeen, Scotland. J Dent Educ 77:1147–1153.

Adamczyk C, Holzer M, Putz R, Fischer MR. 2009. Student learning preferences and the impact of a multimedia learning tool in the dissection course at the University of Munich. Ann Anat 191:339–348.

Allen LK, Eagleson R, de Ribaupierre S. 2016. Evaluation of an online three-dimensional interactive resource for undergraduate neuroanatomy education. Anat Sci Educ 9:431–439.

Al-Rawi W, Easterling L, Edwards PC. 2015. Development of a mobile device optimized cross platform-compatible oral pathology and radiology spaced repetition system for dental education. J Dent Educ 79:439–447.

Azer SA, Azer S. 2016. 3D Anatomy models and impact of learning: A review of the quality of the literature. Health Prof Educ 2:80–98.

Baker EW, Slott PA, Terracio L, Cunningham EP. 2013. An innovative method for teaching anatomy in the predoctoral dental curriculum. J Dent Educ 77:1498–1507.

Bakr MM, Massey WL, Alexander H. 2013. Evaluation of Simodont® Haptic 3D virtual reality dental training simulator. Int J Dent Clin 5:1–6.

Bakr MM, Massey W, Alexander H. 2014. Students' evaluation of a 3DVR haptic device (Simodont®). Does early exposure to haptic feedback during preclinical dental education enhance the development of psychomotor skills? Int J Dent Clin 6:1–7.

Bakr MM, Massey WL, Massa HM. 2016a. Flipping a dental anatomy course: A retrospective study over four years. Educ Res Int 2016:7097398.

Bakr MM, Massey WL, Massa HM. 2016b. Digital cadavers: Online 2D learning resources enhance student learning in practical head and neck anatomy within dental programs. Educ Res Int 2016:8506251.

Bakr MM, Thompson CM, Massadiq M. 2017. Anatomical sciences: A foundation for a solid learning experience in dental technology and dental prosthetics. Anat Sci Educ 10:395–404.

Bell A, Ayoub AF, Siebert P. 2003. Assessment of the accuracy of a three-dimensional imaging system for archiving dental study models. J. Orthod 30:219–223.

Benavides E, Rios HF, Ganz SD, An CH, Resnik R, Reardon GT, Feldman SJ, Mah JK, Hatcher D, Kim MJ, Sohn DS, Palti A, Perel ML, Judy KW, Misch CE, Wang HL. 2012. Use of cone

beam computed tomography in implant dentistry: The International Congress of Oral Implantologists Consensus Report. Implant Dent 21:78–86.

Bodi LH, Turbino ML, Vieira GF. 2007. Evaluation of the effectiveness of the geometric method in the learning of dental sculpture at a dental undergraduate course. Rev ABENO 7:112–116.

Boeker M, Andel P, Vach W, Frankenschmidt A. 2013. Game-based e-learning is more effective than a conventional instructional method: A randomized controlled trial with third-year medical students. PLoS One 8:e82328.

Bogacki RE, Best A, Abbey LM. 2004. Equivalence study of a dental anatomy computer-assisted learning program. J Dent Educ 68:867–871.

Bosse HM, Mohr J, Buss B, Krautter M, Weyrich P, Herzog W, Junger J, Nikendei C. 2015. The benefit of repetitive skills training and frequency of expert feedback in the early acquisition of procedural skills. BMC Med Educ 15:22–31.

Cantin M, Muñoz M, Olate S. 2015. Generation of 3D tooth models based on three-dimensional scanning to study the morphology of permanent teeth. Int J Morphol 33:782–787.

Chen AM, Kiersma ME, Yehle KS, Plake KS. 2015a. Impact of an aging simulation game on pharmacy students' empathy for older adults. Am J Pharm Educ 79:65–74.

Chen AM, Kiersma ME, Yehle KS, Plake KS. 2015b. Impact of the Geriatric Medication Game® on nursing students' empathy and attitudes toward older adults. Nurse Educ Today 35:38–43.

Curnier F. 2010. Teaching dentistry by means of virtual reality--The Geneva project. Int J Comput Dent 13:251–263.

de Azevedo RA, Correa MB, Torriani MA, Lund RG. 2018. Optimizing quality of dental carving by preclinical dental students through anatomy theory reinforcement. Anat Sci Educ (in press; doi: 10.1002/ase.1752).

de Azevedo Rde A, da Rosa WL, da Silva AF, Correa MB, Torriani MA, Lund RG. 2015. Comparative effectiveness of dental anatomy carving pedagogy: A systematic review. J Dent Educ 79:914–921.

de Boer IR, Wesselink PR, Vervoorn JM. 2013. The creation of virtual teeth with and without tooth pathology for a virtual learning environment in dental education. Eur J Dent Educ 17:191–197.

de Wit-Zuurendonk LD, Oei SG. 2011. Serious gaming in women's health care. BJOG 118:17–21.

Del Blanco A, Torrente J, Fernandez-Manjon B, Ruiz P, Giner M. 2017. Using a videogame to facilitate nursing and medical students' first visit to the operating theatre. A randomized controlled trial. Nurse Educ Today 55:45–53.

Douglas RD, Hopp CD, Augustin MA. 2014. Dental students' preferences and performance in crown design: Conventional wax-added versus CAD. J Dent Educ 78:1663–1672.

Drapkin ZA, Lindgren KA, Lopez MJ, Stabio ME. 2015. Development and assessment of a new 3D neuroanatomy teaching tool for MRI training. Anat Sci Educ 8:502–509.

El Tantawi M, Sadaf S, Alhumaid J. 2018. Using gamification to develop academic writing skills in dental undergraduate students. Eur J Dent Educ 22:15–22.

Estevez ME, Lindgren KA, Bergethon PR. 2010. A novel three-dimensional tool for teaching human neuroanatomy. Anat Sci Educ 3:309–317.

Evans DJ, Zeun P, Stanier RA. 2014. Motivating student learning using a formative assessment journey. J Anat 224:296–303.

Fehrenbach MJ, Popowics T. 2016. Illustrated Dental Embryology, Histology and Anatomy. 4 Ed. Maryland Heights, MO: Elsevier Saunders. 352 p.

Guillot A, Champely S, Batier C, Thiriet P, Collet C. 2007. Relationship between spatial abilities, mental rotation and functional anatomy learning. Adv Health Sci Educ Theory Pract 12:491–507.

Hackett M, Proctor M. 2016. Three-dimensional display technologies for anatomical education: A literature review. J Sci Educ Technol 25:641-654.

Hajeer MY, Millett DT, Ayoub AF, Siebert JP. 2004. Current products and practices. J Orthod 31:154–162.

Hegarty M, Keehner M, Khooshabeh P, Montello DR. 2009. How spatial abilities enhance, and are enhanced by, dental education. Learn Individ Differ 19:61–70.

Hoyek N, Collet C, Rastello O, Fargier P, Thiriet P, Guillot A. 2009. Enhancement of mental rotation abilities and its effect on anatomy learning. Teach Learn Med 21:201–206.

Hoyek N, Collet C, Di Rienzo F, De Almeida M, Guillot A. 2014. Effectiveness of three-dimensional digital animation in teaching human anatomy in an authentic classroom context. Anat Sci Educ 7:430–437.

Jackson TH, Hannum WH, Koroluk L, Proffit WR. 2011. Effectiveness of web-based teaching modules: Test-enhanced learning in dental education. J Dent Educ 75:775–781.

Jastrow H, Hollinderbaumer A. 2004. On the use and value of new media and how medical students assess their effectiveness in learning anatomy. Anat Rec 280B:20–29.

Javaid M, Ashrafi S, Žefran M, Steinberg AD. 2016. ToothPIC: An interactive application for teaching oral anatomy. IEEE Trans Learn Tech 9:184–189.

Kato A, Ohno N. 2009. Construction of three-dimensional tooth model by micro-computed tomography and application for data sharing. Clin Oral Investig 13:43–46.

Keedy AW, Durack JC, Sandhu P, Chen EM, O'Sullivan PS, Breiman RS. 2011. Comparison of traditional methods with 3D computer models in the instruction of hepatobiliary anatomy. Anat Sci Educ 4:84–91.

Khatoon B, Hill KB, Walmsley AD. 2013. Can we learn, teach and practise dentistry anywhere, anytime? Br Dent J 215:345–347.

Khatoon B, Hill KB, Walmsley AD. 2014. Dental students' uptake of mobile technologies. Br Dent J 216:669–673.

Khot Z, Quinlan K, Norman GR, Wainman B. 2013. The relative effectiveness of computer-based and traditional resources for education in anatomy. Anat Sci Educ 6:211–215.

Kiely KM, Butterworth P, Watson N, Wooden M. 2014. The symbol digit modalities test: Normative data from a large nationally representative sample of Australians. Arch Clin Neuropsychol 29:767–775.

Kilistoff AJ, Mackenzie L, D'Eon M, Trinder K. 2013. Efficacy of a step-by-step carving technique for dental students. J Dent Educ 77:63–67.

Kron FW, Gjerde CL, Sen A, Fetters MD. 2010. Medical student attitudes toward video games and related new media technologies in medical education. BMC Med Educ 10:50–60.

Krüger JK, Suchan B. 2016. You should be the specialist! Weak mental rotation performance in aviation security screeners - Reduced performance level in aviation security with no gender effect. Front Psychol 7:333.

Kwon HB, Park YS, Han JS. 2018. Augmented reality in dentistry: A current perspective. Acta Odontol Scand (in press; doi: 10.1080/00016357.2018.1441437).

Langlois J, Wells GA, Lecourtois M, Bergeron G, Yetisir E, Martin M. 2015. Spatial abilities of medical graduates and choice of residency programs. Anat Sci Educ 8:111–119.

Llena C, Folguera S, Forner L, Rodríguez-Lozano FJ. 2018. Implementation of augmented reality in operative dentistry learning. Eur J Dent Educ 22:e122–e130.

Lone M, McKenna JP, Cryan JF, Downer EJ, Toulouse A. 2018. A survey of tooth morphology teaching methods employed in the United Kingdom and Ireland. Eur J Dent Educ (in press; doi: 10.1111/eje.12322).

Lone M, Vagg T, Theocharopoulos A, Cryan JF, Downer EJ, McKenna JP, Toulouse A. 2017. Development of an online tooth morphology 3D quiz to enhance dental student learning. In: Gómez Chova L, López Martínez A, Candel Torres I (Editors). Proceedings of the 11th International Technology, Education and Development Conference (INTED 2017); Valencia, Spain, 2017 March 6-8. p 6153–6160. International Academy of Technology, Education and Development (IATED), Valencia, Spain.

Lynch CD, McConnell RJ, Hannigan A. 2006. Dental school admissions in Ireland: Can current selection criteria predict success? Eur J Dent Educ 10:73–79.

Maggio MP, Hariton-Gross K, Gluch J. 2012. The use of independent, interactive media for education in dental morphology. J Dent Educ 76:1497–1511.

Magne P. 2015. A new approach to the learning of dental morphology, function, and esthetics: The "2D-3D-4D" concept. Int J Esthet Dent 10:32–47.

McHanwell S. 2015. Teaching anatomical sciences to dental students. In: Chan LK, Pawlina W (Editors). Teaching Anatomy: A Practical Guide. 1st Ed. New York, NY: Springer International Publishing. p 353–361.

Mitov G, Dillschneider T, Abed MR, Hohenberg G, Pospiech P. 2010. Introducing and evaluating MorphoDent, a Web-based learning program in dental morphology. J Dent Educ 74:1133–1139.

Mowery D, Clayton M, Hu J, Schleyer TK. 2010. Tooth Atlas 3D, version 6.3.0. J Dent Educ 74:1261–1264.

Murphy RJ, Gray SA, Straja SR, Bogert MC. 2004. Student learning preferences and teaching implications. J Dent Educ 68:859–866.

Nagasawa S, Yoshida T, Tamura K, Yamazoe M, Hayano K, Ara Y, Yamada H, Kasahara E, Ito M. 2010. Construction of database for three-dimensional human tooth models and its ability for education and research--Carious tooth models. Dent Mater J 29:132–137.

Nance ET, Lanning SK, Gunsolley JC. 2009. Dental anatomy carving computer-assisted instruction program: An assessment of student performance and perceptions. J Dent Educ 73:972–979.

Nazareth A, Herrera A, Pruden SM. 2013. Explaining sex differences in mental rotation: Role of spatial activity experience. Cogn Process 14:201–204.

Nelson SJ. 2015. Wheeler's Dental Anatomy, Physiology and Occlusion. 10 Ed. St Louis, MO: Elsevier/Saunders. 392 p.

Neubauer AC, Bergner S, Schatz M. 2010. Two- vs. three-dimensional presentation of mental rotation tasks: Sex differences and effects of training on performance and brain activation. Intelligence 38:529–539.

Nicholson DT, Chalk C, Funnell WR, Daniel SJ. 2006. Can virtual reality improve anatomy education? A randomised controlled study of a computer-generated three-dimensional anatomical ear model. Med Educ 40:1081–1087.

Nilsson TA, Hedman LR, Ahlqvist JB. 2011. Dental student skill retention eight months after simulator-supported training in oral radiology. J Dent Educ 75:679–684.

Obrez A, Briggs C, Buckman J, Goldstein L, Lamb C, Knight WG. 2011. Teaching clinically relevant dental anatomy in the dental curriculum: Description and assessment of an innovative module. J Dent Educ 75:797–804.

Perry S, Burrow MF, Leung WK, Bridges SM. Simulation and curriculum design: A global survey in dental education. Aust Dent J 62:453-463.

Peters M, Laeng B, Latham K, Jackson M, Zaiyouna R, Richardson C. 1995. A redrawn Vandenberg and Kuse mental rotations test - Different versions and factors that affect performance. Brain Cognit 28:39–58.

Phillips J, Berge ZL. 2009. Second life for dental education. J Dent Educ 73:1260–1264.

Preece D, Williams SB, Lam R, Weller R. 2013. “Let's get physical”: Advantages of a physical model over 3D computer models and textbooks in learning imaging anatomy. Anat Sci Educ 6:216–224.

Roy E, Bakr MM, George R. 2017. The need for virtual reality simulators in dental education: A review. Saudi Dent J 29:41–47.

Qi S, Yan Y, Li R, Hu J. 2013. The impact of active versus passive use of 3D technology: A study of dental students at Wuhan University, China. J Dent Educ 77:1536–1542.

Salajan FD, Mount GJ, Prakki A. 2015. An assessment of students' perceptions of learning benefits stemming from the design and instructional use of a Web3D atlas. Electron J E Learn 13:120–137.

Sennhenn-Kirchner S, Goerlich Y, Kirchner B, Notbohm M, Schiekirka S, Simmenroth A, Raupach T. 2018. The effect of repeated testing vs repeated practice on skills learning in undergraduate dental education. Eur J Dent Educ 22:e42–e47.

Sheridan LK, Fitzgerald HE, Adams KM, Nigg JT, Martel MM, Puttler LI, Wong MM, Zucker RA. 2006. Normative symbol digit modalities test performance in a community-based sample. Arch Clin Neuropsychol 21:23–28.

Skelton-Macedo MC, Nayyar A. 2013. Perfect tooth. J Dent Educ 77:182–184.

Smith A. 1982. Symbol Digit Modalities Test (SDMT). Los Angeles, CA: Western Psychological Services.

Spallek H, Turner SP, Donate-Bartfield E, Chambers D, McAndrew M, Zarkowski P, Karimbux N. 2015a. Social media in the dental school environment, part A: Benefits, challenges, and recommendations for use. J Dent Educ 79:1140–1152.

Spallek H, Turner SP, Donate-Bartfield E, Chambers D, McAndrew M, Zarkowski P, Karimbux N. 2015b. Social media in the dental school environment, part B: Curricular considerations. J Dent Educ 79:1153–1166.

Vandenberg SG, Kuse AR. 1978. Mental rotations, a group test of three-dimensional spatial visualization. Percept Mot Skills 47:599–604.

Vuchkova J, Maybury TS, Farah CS. 2011. Testing the educational potential of 3D visualization software in oral radiographic interpretation. J Dent Educ 75:1417–1425.

Wallen ES, Schulein TM, Johnson LA. 1997. A computer program to aid in visual concept development in dentistry. Comput Methods Programs Biomed 52:105–115.

Wright EF, Hendricson WD. 2010. Evaluation of a 3-D interactive tooth atlas by dental students in dental anatomy and endodontics courses. J Dent Educ 74:110–122.

Table 1
Characteristics of Participants

Cohort	**2017**	**2016**
Number of participants	59	64
Age (mean ± S.D.)	22.8 ± 3.7	21.5 ± 3.9
Sex (female / male)	44/15	45/19
Region of origin		
Europe, N (%)	29 (49.2)	44 (68.8)
Canada, N (%)	18 (30.5)	16 (25.0)
Asia, N (%)	11 (18.6)	4 (6.2)
Middle East, N (%)	1 (1.7)	
Academic programme		
Direct entry dental student, N (%)	34 (57.7)	40 (62.5)
Graduate entry dental student, N (%)	14 (23.7)	10 (15.6)
Dental hygiene student, N (%)	11 (18.6)	14 (21.9)
Education level completed		
Secondary level, N (%)	27 (45.8)	-
Third level, N (%)	24 (40.7)	-
Not specified, N (%)	8 (13.5)	-
[a]SDMT score, mean ± S.D. (range)	57.5 ± 9.4 (41.8-90.9)	-
[b]MRT score, mean ± S.D.(range)	42.2 ± 23.0 (0-83.3)	-

[a]Maximum possible score on SDMT is 110 (the results are reported as the percentage of correct answers); [b]Maximum possible score on MRT is 24 (the results are reported as the percentage of correct answers); N, number of participants; SDMT, symbol-digit modality test; MRT, mental rotation test version A; S.D., standard deviation.

Table 2
Gender differences in performance

Characteristics	Female (N = 44) (mean ± S.D.)	Male (N = 15)) (mean ± S.D.)	t value	*P* value
Age	22.6 ± 3.9	23.3 ± 3.0	0.671	0.505
[a]SDMT	57.5 ± 8.4	57.5 ± 12.3	0.001	0.999
[b]MRT A	36.6 ± 22.4	58.6 ± 17.3	3.516	**0.0009**
3D teeth Mock 1 (%)	34.1 ± 14.0	51.3 ± 19.2	3.417	**0.001**
Extracted teeth Mock 1 (%)	40.2 ± 17.5	58.7 ± 18.9	3.464	**0.001**
Total Mock 1 (%)	37.2 ± 15.0	55.0 ± 15.9	3.926	**0.0002**
3D teeth Mock 2 (%)	43.2 ± 19.4	48.7 ± 20.3	0.935	0.353
Extracted teeth Mock 2 (%)	51.4 ± 19.5	62.7 ± 22.8	1.857	0.068
Total Mock 2 (%)	47.3 ± 15.5	55.7 ± 19.5	1.691	0.096
Final examination (%)	73.6 ± 13.2	80.1 ± 13.7	1.632	0.108

[a]Maximum possible score on SDMT is 110 (the results are reported as the percentage of correct answers); [b]Maximum possible score on MRT is 24 (the results are reported as the percentage of correct answers); N, number of participants; SDMT, symbol-digit modality test; MRT, mental rotation test version A; S.D., standard deviation.

Table 3
Participants' qualitative feedback

Items	**Mean ±*SD*)[a]**
Group 1: Ease of use of the TMQ app (Cronbach's α = 0.64)	***3.57 (±1.10)***
The tooth morphology app was easy to use	3.19 *(±1.02)*
I was able to use the app without assistance	4.11 *(±1.05)*
The app was easy to understand and follow	3.75 *(±0.87)*
I found this app very confusing as compared to the extracted teeth	2.77 *(±1.17)*[b]
Group 2: Quality of the images (Cronbach's α = 0.29)	***2.76 (±1.07)***
The image quality was poor	3.02 *(±1.10)*
There was distortion in the 3D images	2.51 *(±0.97)*
Group 3: Ease of tooth manipulation (Cronbach's α = 0.69)	***2.96 (±1.19)***
The 3D aspect of the application was easy to understand	3.58 *(±0.99)*
The 3D tooth was easy to orient (Upper/lower, right/left)	2.66 *(±1.16)*
It was easy to orientate the tooth	2.64 *(±1.18)*
Group 4: Quality of the features of the teeth (Cronbach's α = 0.71)	***3.26 (±1.09)***
The 3D tooth did not resemble the extracted teeth	2.75 *(±1.05)*[b]
The app showed the key identifying features of the teeth clearly	3.21 *(±0.97)*
The cusps and grooves on the occlusal surface of the crown were clearly visible	2.77 *(±1.15)*
The roots of the teeth were not clearly visible	2.26 *(±1.18)*[b]
The visible features helped me identify the correct teeth	3.34 *(±0.90)*
Group 5: Usefulness as a tooth morphology learning tool (Cronbach's α = 0.86)	***2.96 (±1.10)***
The app improved my confidence in identifying the teeth	2.62 *(±1.02)*
The 3D aspect of the application helped with learning tooth morphology	3.04 *(±1.06)*
The app is a not a useful learning resource	2.77 *(±1.14)*[b]
Group 6: Comparison with extracted teeth as a learning tool (Cronbach's α = 0.62)	***1.92 (±1.11***
The app provided a better learning experience than extracted tooth	1.81 *(±0.81)*
I learned more from manipulating extracted teeth than from the app	4.36 *(±1.08)*[b]
I prefer to hold/visualize the extracted teeth while learning tooth morphology	4.62 *(±0.69)*[b]
I prefer not to look at 3D images of the teeth	2.85 *(±1.20)*[b]
Group 7: Enjoyment factor (Cronbach's α = 0.78)	***3.59 (±1.07)***
I enjoyed using this application	3.19 *(±0.94)*
I would like to have this app on my laptop	3.64 *(±1.15)*
This app should be available online and accessible at all times	3.94 *(±1.01)*

Group 8: Usefulness of feedback provided (Cronbach's α = 0.89)	***3.56 (±1.08)***
The feedback at the end was very helpful	3.68 *(±1.12)*
The feedback improved my understanding of the tooth morphology	3.64 *(±3.64)*
The feedback provided at the end helped improve my score for my next quiz	3.36 *(±1.04)*
Group 9: Usefulness of quizzes (Cronbach's α = 0.73)	***3.69 (±0.92)***
I don't enjoy self-test quizzes	2.09 *(±0.84)* [b]
I would like to use the quiz again	3.21 *(±0.93)*
I like self-assessment and use quizzes to help me study and test myself	3.72 *(±0.97)*
Quizzes are helpful for self-assessment and understanding of the topic	4.02 *(±0.80)*

[a]Based on a five-point Likert scale (1 = strongly disagree, 2 = disagree, 3 = neutral, 4 = agree, and 5 = strongly agree). [b]The Likert scale data for this item was inverted when used for Cronbach's α and group mean calculation. The numbers in bold indicate the mean for the statements of the group.SD, standard deviation.

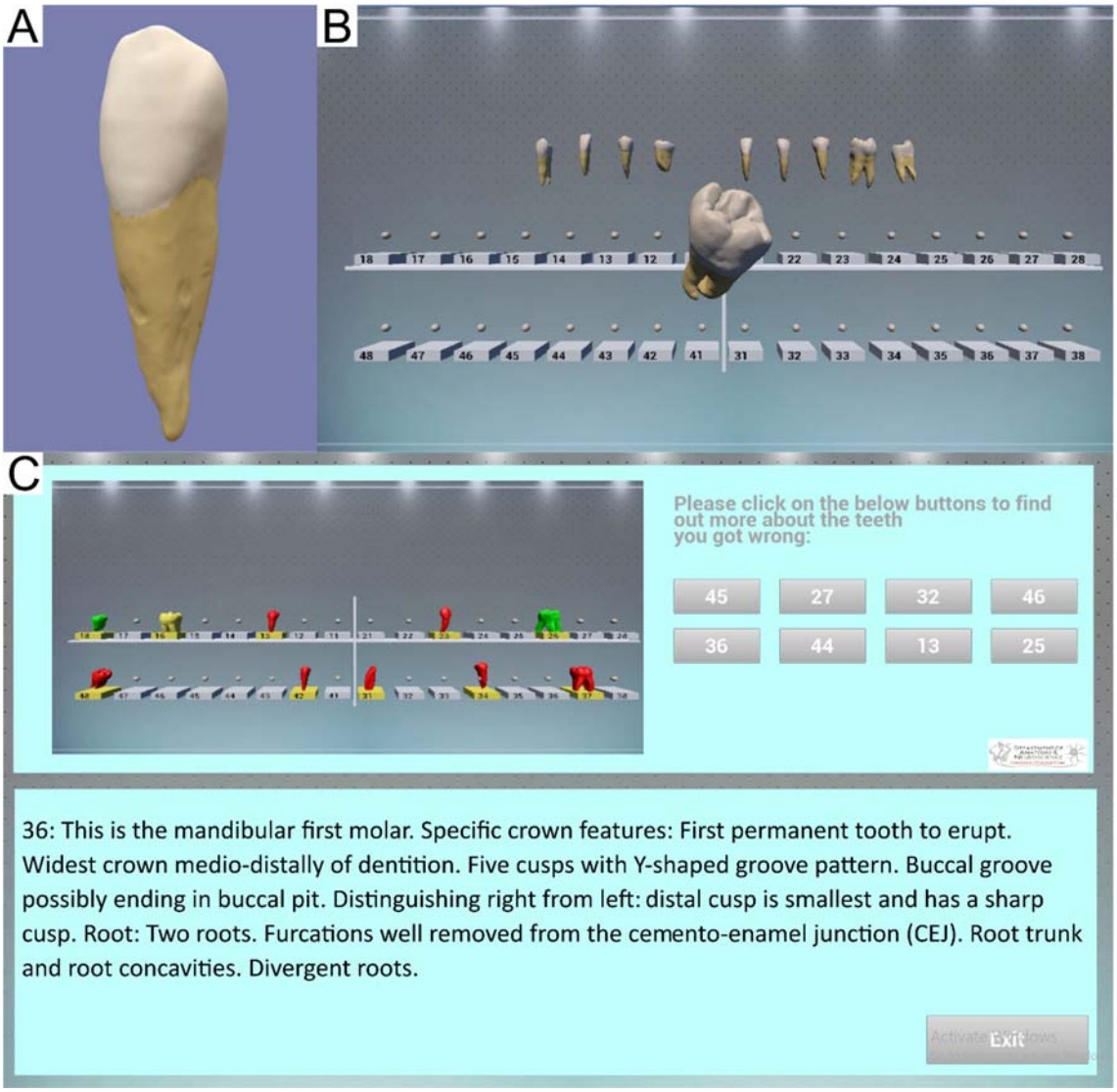

Figure 1. Representative images of the Tooth morphology Quiz (TMQ) environment. A, Representation of a digitalized and colored adult lower lateral canine (LL3) prior to insertion in the TMQ environment. B, Representation of the working screen. The user is presented with 10 randomly selected teeth that must be placed in the Fédération Dentaire Internationale (FDI) charting system. A tooth has been selected for closer inspection. C, Representation of the end panel. The correctly placed teeth are illustrated in green and incorrect ones are illustrated in red. After selection of one of the incorrectly placed teeth, it is highlighted in yellow and feedback on its distinguishing features is provided.

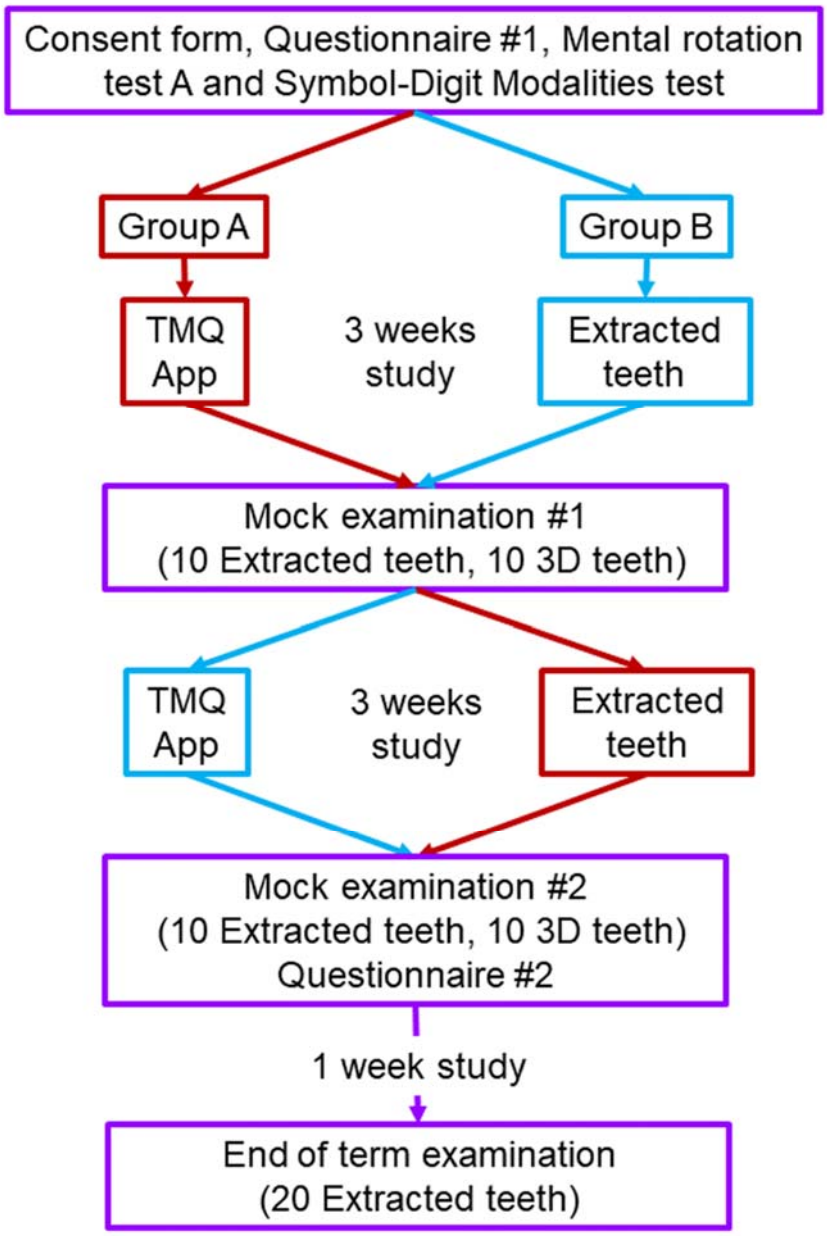

Figure 2. Schematic representation of the study design. Group A is represented by red lines and boxes while group B is represented in blue. Elements completed by both groups simultaneously are presented in purple.3D, three-dimensional; TMQ, Tooth Morphology Quiz

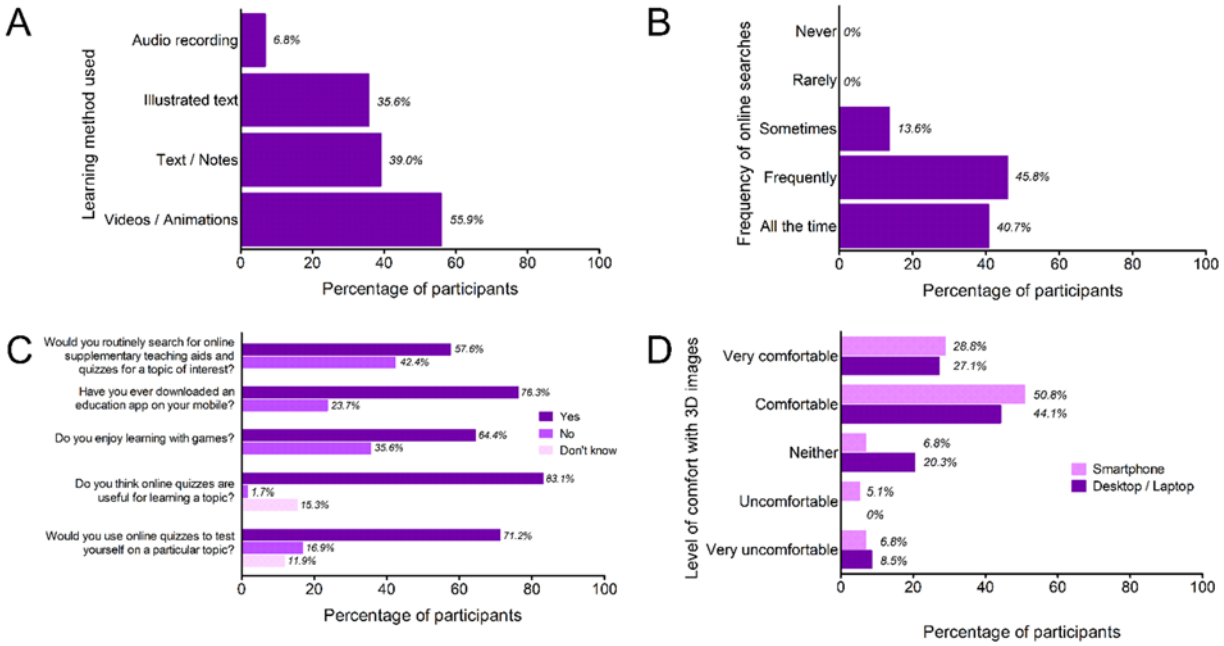

Figure 3. Participants usage of electronic devices and learning preferences. A, The participants were asked to select, from a list of options, the learning methods that they use while studying. B, The students were asked to indicate on a Likert-type scale how frequently they perform an online search when studying a new or difficult topic. C, The participants were asked to answer a series of 5 questions pertaining to their usage of online learning tools. D, The students were asked to indicate on a Likert-type scale how comfortable they feel when manipulating three-dimensional images on a computer or a smartphone. For each panel, the results are expressed as the percentage of respondent in each category (N=59).

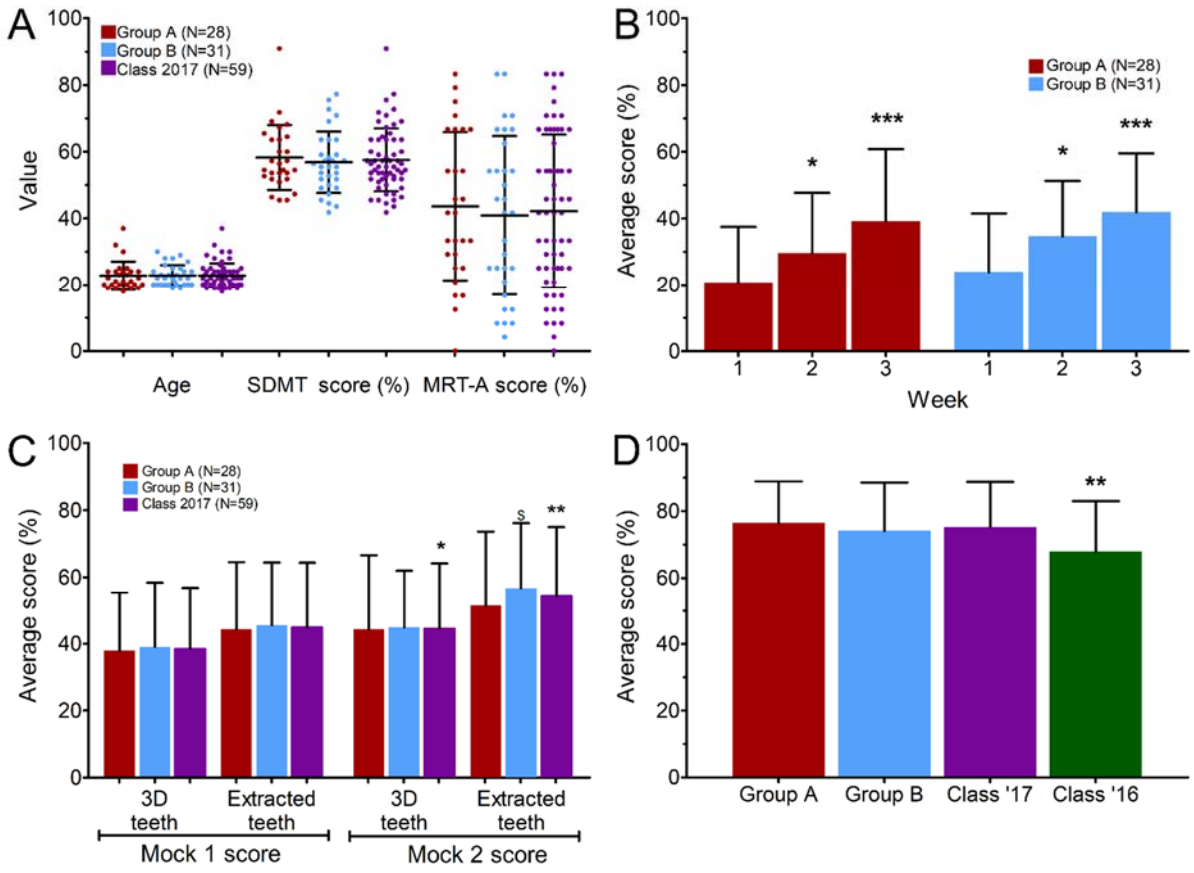

Figure 4. Groups performance in assessment. A, Groups profile. The graph shows the age, Symbol-Digit Modalities Test (SDMT) and Mental Rotation Test version A (MRT-A) scores distribution of groups A and B as well as that of the 2017 class. The data are presented as a distribution plot with the mean ± S.D. indicated by horizontal bars. The scores for the SDMT and MRT-A tests are reported as the percentage of correct answers achieved by each student. There are no significant differences between groups A, B and the class ($P > 0.05$, ANOVA with Bonferroni *post-hoc* test for each category). The number of participants in each group is indicated on the graph. B, Groups performance on the Tooth morphology Quiz (TMQ) app. Each group had access to the app for three consecutive weeks (1h / week). The mean score for each week and group is presented ±SD. The data show a significant increase after each week of usage ($P < 0.0001$, one-way ANOVA with Dunnett's post-hoc analysis, $^{*}P < 0.05$ and $^{***}P < 0.001$ compared to the results of week 1 for each group).C, Groups performance in mock examination. For each mock assessment, the students had to identify 10 extracted teeth and 10 3D digitalized teeth. The data are presented as the mean percentage score of each group ± SD. The graph shows significant increase in class average between mock assessments 1 and 2 ($^{*}P < 0.05$ and $^{**}P<0.01$, paired Student's *t*-test). Results breakdown shows that students significantly improved in the second mock assessment for extracted tooth identification ($^{\$}P < 0.05$ compared to the same category in mock assessment 1, paired Student's *t*-test). D, Class performance in mock and end-of term examination. For each mock assessment, the students had to identify 10 extracted teeth and 10 3D digitalized teeth. The data are presented as the mean percentage score of each group ± SD. ($^{**}P < 0.01$ compared to the 2017 class, unpaired Student's *t*-test).

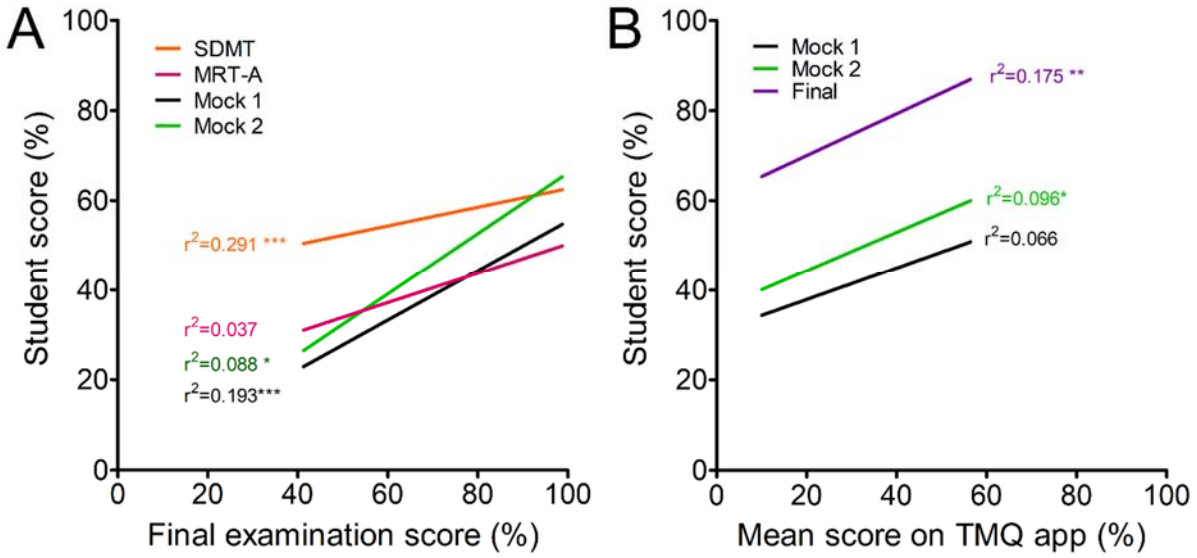

Figure 5. Performance at various stages of the study predicts assessment outcomes. A, Student's performance on mock assessments 1 and 2 was positively correlated with final examination score (***$P < 0.001$, Pearson correlation). The participants' score on the final assessment was also positively correlated with Symbol-Digit Modalities Test (SDMT) score (*$P < 0.05$, Pearson correlation) but not with Mental Rotation Test (MRT-A) performance. B, Student's performance on the Tooth Morphology Quiz (TMQ) is positively correlated with scores on final examination and mock assessment (*$P < 0.05$, **$P < 0.01$, Pearson correlations).