Combining Virtual Reality and 3D Printed Models to Simulate Patient-Specific Dental Operative Procedures – A Study Exploring Student Perceptions.

Abstract

Introduction

Students face a number of challenges in translating skills acquired in pre-clinical simulation environments to the delivery of real patient care. These are particularly emphasised for complex operative procedures such as tooth preparations for indirect restorations. This paper reports student perceptions of a novel approach designed to improving student confidence when undertaking operative procedures on patients for the first time, by providing patient-specific simulation using Virtual Reality (VR) and 3D printed models of the student's real clinical case.

Methods

Students practised on patient-specific models, in the presence of a clinical tutor, firstly using VR simulation then with 3D printed models in a clinical skill laboratory. The students then carried out the operative procedure on their real patients, on the third occasion of practice. After providing the treatment for their patients, students attended a semi-structured interview to discuss their experiences. The qualitative data was analysed using two forms of inductive analysis.

Results

Students most frequently cited: the value of the educator, increased confidence and efficiency during the clinical procedure, improved patient confidence and the complementary benefits of the two simulation modalities.

Thematic analysis of participants' responses uncovered five key themes:

- The value of virtual reality dental simulators
- The value of clinical skills laboratory simulation with 3D printed models
- The value of educator engagement
- The impact on the clinical procedure and the patient
- The VR and clinical skills laboratory balance

Conclusion

This paper reports the early findings of an intervention that improves dental student confidence through the use of patient-specific VR exercises and 3D printed models. These provided an incremental learning experience for an operative clinical procedure, prior to treatment of the live patient. Early results suggest this is a positive experience for the students, providing a valuable contribution to their confidence and preparedness.

Key words: dental education, virtual reality, three-dimensional printing, tooth preparation dental care

Introduction

In order to provide safe and effective dental care for patients, dental students must develop competence in the provision of operative dental procedures [1, 2]. The process of learning these operative procedures is complex and involves the acquisition and development of knowledge and motor skills. These operative dental skills are commonly learned through training in a simulated clinical environment.

Students typically practice operative dental skills using extracted human or artificial teeth that are set up in a 'phantom head' simulator in a clinical skills laboratory [3]. Whilst these are useful for developing operative skills, the variation in condition of extracted teeth and the inherent standardisation of form and hardness of typodonts means that these can only provide the student with an indicative 'generic' experience of what will be encountered when undertaking the real procedure. These limitations mean that there is still a significant transition, or 'gap', between simulated practice cases and actually providing the treatment on real patients [4]. This challenging transition appears to be particularly emphasised with more complex operative procedures, including tooth preparation for indirect restorations. It has been reported that students and recent graduates have a low level of confidence and preparedness when carrying out these procedures [5-7].

Confidence is defined as the belief in one's abilities to accomplish a goal or task [8]. In this context, Morgan & Cleave-Hogg [9] showed a significant correlation between the number of times a skill or procedure was performed and the increased level of confidence reported by the individual student. Taking this a step further, students' confidence in their ability to undertake dental procedures, correlates with an increase in confidence in communication skills and leads to improved patient satisfaction [10]. Thus, undertaking a procedure multiple times leads to an increase in reported confidence, that in turn leads to the ability to undertake other concurrent clinical procedures more effectively. A reasonable assumption arising from this, is that confidence acquisition is important in the development and improvement of overall student performance in a clinical setting.

This transition between the experience gained by a student in the pre-clinical environment and their ability to confidently translate these skills to a patient-centred clinical environment has been well reported in dental education literature [4, 11-13]. This aspect of their training is particularly challenging for dental students and clinical practice has been highlighted as a common source of stress [14, 15]. Therefore, any educational initiatives that can reduce this stress and improve student confidence would be welcomed by dental educators and students alike.

Deliberate practice is a useful educational theory that can be used to support students in learning these complex operative skills. This involves the development of a desired skill through tailored practice. The practice should have a well-defined goal, be motivating, have immediate feedback and allow for repetition of the task [16]. However, the differences between the simulated environment and real patient presentations, mean that the advice offered by tutors during simulation can only be generic rather than tailored to the specific challenges that students may face.

Whilst Virtual Reality (VR) simulation is a relatively recent addition to the methods available to educators in the training of dental students, their value has been demonstrated as equivalent to the use of phantom heads for training cavity preparation skills [17]. Additionally, by combining VR simulation with patient impressions, it is possible to create exercises where students can practice the actual case they will encounter with their patient [18]. This may allow students to deliberately practice the procedure they will undertake; recognise the difficulties they may encounter and potentially lead to a better outcome for their patient. However, a number of core operative concepts are currently under-represented in the hardware of the VR simulated environment. This may mean there are still aspects of the intervention that the students have not been able to prepare for, such as, where they will achieve a suitable finger rest, the use of indirect vision or the retraction of the oral soft tissues [19, 20].

Elsewhere, patient scans have been combined with 3D printed models to provide a more authentic representation of the oral cavity than normal typodonts [21-23]. 3D printed models compare well against cadaveric models [23] and have also been shown to be effective for training advanced procedures such as crown preparations [24] and intra-radicular post preparations [25]. However, whilst the 3D printed models in these studies were based on real patient cases, they were not exact replicas of the specific patient case for which individual students would undertake the operative procedure.

Combining, and building upon, these two previous approaches by allowing students to engage in deliberate practice on both a patient-specific VR exercise and 3D printed models of the actual case that the student will encounter in clinic has not, to date, been investigated. It is possible that each modality can offer a unique insight into preparing for the intervention and combined, additional and accelerated skill acquisition may occur. This enhanced learning experience has the scope to increase student confidence in their ability to undertake the actual ‘rehearsed’ operative task and the clinical event as a whole.

This study aims to pilot an educational initiative by combining patient-specific VR exercises and 3D printed models, in order to improve student confidence when preparing teeth for indirect restorations on patients. Ultimately, this study begins to address the challenge set by Al-Saud [26] to investigate enhancing motor skill acquisition through the use of multimodal simulation, combining the best features of VR and traditional approaches.

Aims

The aims of this study to are:

- To explore whether an incremental learning approach using VR and 3D simulation of patient-specific cases impacts on student confidence
- To report early student perceptions of this approach

Methods

This study received ethical approval from the research ethics committee at the School of Clinical Dentistry, University of Sheffield (project number 023486).

Students from both undergraduate and postgraduate dental programmes were invited to take part in the study by email. Students were eligible to participate in the study if they had completed a pre-clinical operative skills training course and were planning to prepare a tooth for an indirect restoration on a patient in the near future.

To confirm that students were eligible to participate and that their patient case was suitable for use in the study, the prospective participant presented their patient case to a clinical member of the project team (JD, NM). Once suitability was confirmed, informed consent was obtained from the patients and students involved. Students then obtained patient records including intraoral photographs and either a sectional impression with a polyvinyl siloxane impression material (Aquasil, Dentsply Sirona, USA) or an intra-oral scan (Primescan, Dentsply Sirona, USA). The choice between conventional and digital impressions was determined by the availability of the equipment at the time of record taking.

Where a silicone impression was taken, a study model was poured and this was scanned using an Identica Blue (Medit, Seoul, South Korea) model scanner to create a stereo lithography (stl) file. When an intra-oral scanner (Primescan, Dentsply Sirona, USA) was used, the digital file was acquired directly, without the need for additional steps of pouring and scanning a study model.

After the acquisition of the digital file, post-processing was carried out using Autodesk MeshMixer (California, United States) to prepare the digital model for printing and creating a VR simulator exercise; this included:

- Trimming the model to include the relevant working area
- Closing gaps in the model and removing any artefacts from the acquisition process
- Converting the model from a surface scan to a solid object

- Digitally recreating the interproximal spaces lost during scanning (see discussion)
- For the 3D printed model only, the addition of LEGO™ inspired holes to aid with retention in the wax arches

The model was then printed using a FormLabs Form 2 printer (Massachusetts, United States) using standard Grey resin (FormLabs product code: RS-F2-GPGR-04). Defaults were accepted for the printer settings.

Finally, the same stl file was imported into HRV Solid Editor (Laval, France) to create the VR exercise. The entire model was set to be composed of a single material with hardness similar to human enamel. Other than an exercise identifier and brief description, no other configuration was performed in Solid Editor prior to exporting the exercise to the simulators. This process is summarised in

Figure 1.

When both models were ready, participating students were invited to attend two separate simulation sessions, first using a HRV Virteasy dental skills trainer (Laval, France) (Figure 2) and subsequently using the 3D printed models that were mounted in a phantom head in the clinical skills laboratory (Figure 3). Each session was up to one hour long and a clinical member of staff was present for the duration to provide clinical feedback and guidance on the student's attempts at the preparations. All student participants were familiar with and had previously used both the VR systems and the clinical skills environment prior to the study.

As this project used cutting edge approaches in both VR and 3D printing for dental education, a decision to adopt the on-the-fly approach [27] was taken. This allowed adaptations to the simulation experience to rapidly resolve any issues that would detract from the exploration of the intervention itself. Examples of these adaptations included adding retentive features to retain the model in the phantom head and allowing participants to edit the simulator configuration to suit individual preferences with regard to material density and calibration.

Following the simulation sessions, participants undertook the same operative procedure for their patients in a supervised clinical session. Participants were then invited to attend a short semi-structured interview with a study investigator. This student-led interview aimed to uncover the perceptions of students regarding this approach and students were prompted to discuss freely across four key concepts: the value of both VR and clinical skills laboratory simulation, the need for an educator to be present in the simulation sessions and the impact of the simulation on the clinical procedure.

Interviews were recorded (audio only) on a secure device, transcribed and subsequently the original recordings were destroyed. Neither the VR or 3D printed models contained any identifiable data and were disposed of after the study.

The qualitative data obtained from the interview transcripts was analysed using two different inductive analytical strategies; content analysis and thematic analysis. Both approaches were undertaken independently by two researchers (AT, JD) and the results were subsequently shared and discussed until an agreement was reached. Final analyses were performed once agreement had been established. Firstly, a content analysis of the grounded theory approach was undertaken [28, 29]. This involved analysing the data using initial coding [30] which allowed for a more quantitative analysis of the data by presenting the 'groundedness' or prevalence of each code. NVivo (QSR International) was used to code the data. Data saturation for the content analysis was assessed by establishing when the final new code presented in the data. Subsequently, thematic analysis of the data following the methodology described by Braun and Clarke [31] was used. This is a six-stage process that involves increasing familiarity with the data, establishing preliminary codes and a review process prior to defining the themes [31]. Thematic analysis places greater value on the importance of individual data entries, rather than exclusively focusing on data prevalence. The authors considered that given the semi-structured nature of the interviews, the two approaches were appropriate and complementary so that important, but less frequently reported, points were not missed.

Results

A total of eight students participated in this study (five male, three female). Seven of the participants were undergraduate dental students and one was a student on a postgraduate clinical doctorate programme (Prosthodontics). The participants used the approach in this study to practice the following preparations:

- Porcelain fused to metal crown (3)
- Full gold crown (2)
- Lithium disilicate crown (1)
- Lithium disilicate onlay (1)
- Porcelain fused to metal fixed dental prosthesis (1)

The coded themes and their groundedness (prevalence) taken from the content analysis using NVivo (QSR International) is shown in Table 1. Data saturation was achieved after data analysis of the sixth student, however analysis continued for all 8 participants.

Thematic analysis of participants' responses uncovered five key themes:

- The value of virtual reality dental simulators
- The value of clinical skills laboratory simulation with 3D printed models
- The value of educator engagement

- The impact on the clinical procedure and the patient
- The virtual reality and clinical skills laboratory balance

The themes and a selection of quotes from participants of the study are presented in Table 2.

Discussion

This exploratory action research aimed to explore the potential impact of an educational initiative that bridges the learning gap between core skill acquisition in operative dentistry, and subsequent translation into a patient-centred clinical setting. Through the innovative combination of digital patient intraoral scans, 3D printed models and VR simulation of the actual patient-specific procedures, students were able to engage in deliberate practice, supported with tutor guidance, to rehearse the actual procedure in an iterative manner.

The two methods employed to analyse the qualitative data from the transcribed interviews aimed to provide a broad, unrestricted, view of the impact of the intervention on student confidence. Both analyses were inductive in nature, meaning that analysis was approached with no predetermined themes or theories [29]. Both the content and thematic analysis are similar, in that there is a process of familiarisation with the data and establishing codes that emerge from the data [31, 32]. The content analysis employed provides a frequency value for each code, whereas the thematic analysis develops overarching themes from the data by considering each data entry independently. The results from both analyses should be considered together, rather than as separate entities and therefore the discussion will follow the themes acquired from the thematic analysis (Table 2) whilst integrating the results of the content analysis (Table 1) within it.

The value of virtual reality dental simulators

The importance of establishing a safe finger rest and an ergonomic working position is stressed in operative dental skills courses and textbooks [33, 34] and 75% of the participants mentioned that the VR simulation experience had an impact on this. Participants initially reported difficulties in establishing a comfortable finger rest, however, the VR simulator finger rests are somewhat different to those encountered when working operatively [20]. Properly calibrating the simulator for the individual user resolved this issue. Interestingly, the discussion around these difficulties was presented as a positive because it highlighted the importance of a basic skill that is sometimes taken for granted by more senior students. This renewed emphasis was then specifically considered by the students when moving on to the clinical skills laboratory.

The VR simulators also encouraged participants into adopting an ergonomic operating position (n=6). A computer monitor has a limited range of viewing angles where the image is clearly visible, and this monitor is positioned so that the operator receives the optimal view when seated correctly. To ensure they had the best view of the working area possible, the participants found that they had, subconsciously, adopted a desirable operating position.

Participants enthusiastically discussed how the most useful application of the VR simulation was in the planning of the procedure (n=5) and how it allowed them to “play” with different techniques and approaches (n=4). The VR model of their patient allowed them to zoom in and aid in their understanding of the tooth’s anatomy, plan how they would manage the difficult-to-access areas, anticipate challenges and experiment with different instruments and techniques to address them. This knowledge was then taken to the clinical skills laboratory where it could be built on with further practice on the 3D printed models. These findings add weight to similar results by Serrano *et al.* [18] and further strengthens the case for the use of VR simulation as a controlled, transitional, environment where risks can be mitigated and safety increased through deliberate, patient-specific, practice.

Some of the earliest goals for VR in dental education were to provide a safe, clean and distraction free environment where there was no incremental cost for resetting to make another attempt [35]. Comments from the participants strongly support that this has been achieved and that they were able to spend more time on-task than they were able to in other environments. However, one area where the VR exercises produced for this work deviate from these original goals is that they do not contain a target area or predefined “ideal” preparation for comparison with the student’s performance. The only metric available is the percentage of material removed. However, most participants (n=5) reported that they found this quantitative measure useful, as when combined with the measurement tools and cross-sectional views it helped guide the tooth reduction and allowed them to better appreciate the substantial amount of tooth structure removed during tooth preparation.

Most participants (n=5) commented that the tooth hardness was not realistic in the VR simulation. However, there was some disagreement between the students as to whether the tissue was too hard or too soft. This disagreement has been seen elsewhere in the literature; in the calibration of their VR simulator’s hardness settings Wang *et al.* [36] found a wide range of opinions for what the correct setting should be. Likewise, Konukseven *et al.* [37] found that participants wanted to tailor the density values of simulated teeth to their own preferences. It is known that there are naturally occurring variations in the density of enamel [38] but a VR simulation will always be compared to the subjective mental model of the individual operator’s view of what that density should be. This presents a difficulty for the designers of VR simulators because, even when the system’s density settings fall within the normal range of natural enamel, they must somehow correspond with the subjective view of the correct values held by the individual operator [39]. Further studies should be carried out into the subjectivity of these values to investigate if additional calibration is needed to improve acceptance for more experienced users.

The value of clinical skills laboratory simulation with 3D printed models

Students highlighted that they found practicing the operative procedure on the 3D printed models very useful. Most participants (n=6) stated that it felt like a "trial run" of the clinical procedure and, agreeing with findings by Höhne *et al.* [24], found the 3D printed model of their patient's teeth preferable to a standard, generic, model. Using real instruments and having to establish finger-rests on the same structures as would be available in the real case made the experience feel highly authentic.

Students felt that the 3D printed material had an acceptable hardness (n=6) and cut well with rotary instruments providing an adequate representation for practising the procedure. Interestingly, the material itself is known to be softer than natural tooth tissue, however this was overall seen as a positive as students felt they could easily adapt by applying less pressure with the handpiece or it allowed them to work faster and focus on the form of the preparation. This response is in contrast to the student's views of the material hardness of the models used in VR, where the unrealistic feel of the material in VR was considered a negative. It is unclear why this was the case.

Some students found that the dark colour of the grey resin used for the 3D printed models presented issues in distinguishing between the hard and soft dental tissues (n=4). Following the on-the-fly approach [27], an adaptation was made to minimise the issue whereby the wax used to secure the model in the phantom head was extended to cover the printed section of gingivae providing a contrasting colour. During this project, some anecdotal work was undertaken to investigate different 3D printer resins, but the available white resins were found to have poor contrast and were harder to distinguish between tissues than the grey colour. A future, thorough, investigation of what the optimal material for creating practice models would be a welcome addition to work in this area. Such a study should ideally encompass the physical feel and appearance of the material, but also take note of the benefits of a softer material noted above and appropriately frame the evaluation in the educational context that the material will be used.

Early participants (n=3) complained that the contact area between adjacent teeth was fused in the printed models. This meant that adjacent teeth were physically joined by the printed material, leaving no interproximal space, and led to both an unsatisfactory aesthetic appearance and issues in simulating a contact point breakthrough. This fused contact area resulted from the way that the 3D models were acquired. The material used for poured study models would flow into the gaps and fuse the area in the resultant model. This fused material would then be recreated when the model was scanned digitally. Similarly, the intraoral scanner, whilst producing a model with superior definition and a smaller fused area, was not able to fully penetrate the interproximal space. Again, this resulted in a model with a fused area between the teeth. To address this limitation for later participants, the contact area and the interproximal space were recreated digitally using 3D editing software prior to the printing of the physical models.

The value of educator engagement

The joint-highest reported factor (n=7) was how important the participants found the tutor's presence in both simulation environments. It is well established that educational feedback should be timely, meaningful and actionable[40] and participants found that the tutor was able to identify potential problems and break down the complex procedure into smaller, more manageable steps, which facilitated their understanding of the importance of each step. The presence of the tutor during this 'experimental' stage also allowed the identification of errors and explanation of the appropriate corrective action, which is a task students often find difficult on their own [41].

The lack of the availability of tutor supervision is regularly cited as an area where automatically generated feedback from VR simulators can be advantageous [42-44]. However, the strong presence of this feedback suggests that students still place a high value on the presence of a tutor. Perhaps further supporting the view that the optimal approach for VR based training is a combination of automated feedback supported by input from instructors [26]. Although recent developments in providing clinically relevant feedback with dental simulators may impact on this preference as the technology improves [45].

The impact on the clinical procedure and the patient

As a result of their simulation experiences, an increase in both confidence and efficiency to undertake the definitive patient-based procedure was noted by 88% of participants. This manifested itself through the simulation being regarded as a way the student could rehearse each step of the procedure and visualise what they would do during the clinical procedure itself. Consequently, this enabled them to better direct their dental assistant, be more organised and have a more established plan during the clinical procedure itself.

Notwithstanding this, it is important to note that confidence in this context does not necessarily relate to competence. An operator's competence as a measure of the provision of an operative procedure is complex and consists of a range of variables including their knowledge, dexterity, experience, resources, time as well as confidence. It is therefore not surprising, that some studies report a poor correlation between self-reported confidence and competence in tasks such as performing basic operative procedures [46], technical ability [47], or prescribing skills [48, 49]. However, both Clanton *et al.* [50] and Crooks *et al.* [51] note a direct relationship between self-confidence and effective performance, where confidence was reported as an outcome of having achieved further training, as per the simulation undertaken by the students in this study.

Most participants (n=6) reported that taking part in the simulated case prior to the patient case resulted in an improved patient experience. The student was able to work more efficiently and confidently which improved their patient's comfort during the procedure. Participants reported that they were able to share their experiences of completing the procedure in the simulation environment with their patient prior to treatment. This increased the confidence and trust the patient had in the student meaning they were more relaxed during the procedure. This agrees with findings by Clanton *et al.* [50] and Crooks *et al.* [51] that the increase in confidence and effectiveness in the management of the patient-based clinical procedure from further training directly translated to an improved patient clinical experience with better communication, greater trust and a more relaxed state of mind during the definitive procedure.

The use of the patient-specific model was viewed as an essential aspect of the preparatory work by most of the participants (n=5). This is in line with the findings by Serrano *et al.* [18] that students value being able to practice the actual procedure they will be carrying out in a safe and risk-free environment. The addition of the 3D printed model in our study provided an additional intermediate step between the VR simulation and the patient case that the participants found to be more realistic (n=6) than VR and allowed a different skills focus.

The virtual reality and clinical skills laboratory balance

Of the two modalities, most students preferred the 3D printed model in the clinical skills laboratory, although it was suggested that this may be due to their greater familiarity with this environment. However, many students felt (n=6) that there was greatest value in using the two modalities together as they each bring different but complementary advantages in helping to prepare for a clinical case. Using both forms of simulation required a significant time commitment, but most students (n=6) felt that it was worth the time invested.

The use of VR eased the learning curve (n=4) and allowed the participants to freely experiment with different approaches in an environment where the cost of resetting for another attempt was at its lowest. The lessons learnt in this modality could then be taken to the clinical skills laboratory where an incrementally greater 'cost' of failure was introduced due to the limited number of available 3D models.

Using two simulations further highlighted the value of allowing time for student reflection on performance and how operator improvement can result from this. An unintended consequence of the methodology, with an overnight time delay between the simulation exercises, was that it gave the participants time to process and reflect on what had been learned and gain the maximum benefit of their practice session overnight [52, 53]. The value of reflection and allowing time to reflect is known to have a positive impact upon performance and is a core skill required by the General Dental Council (UK) for graduating dentists [54].

This ability to incrementally build on each step in the process and enable the student to reflect upon and refine their approach, building confidence, could be due to a reduction in the cognitive load of the task [55]. Each step in the process detailed above permits a different focus, reducing the overall *extraneous* cognitive load placed upon the student increasing their working memory available for more efficient learning. Using the VR environment first removes some of the considerations and factors that would ordinarily need to be accommodated by the learner in the clinical skills laboratory environment. This reduces the *intrinsic* cognitive load of the task, providing additional cognitive resource for the *germane* load necessary for problem solving and learning from the experience. When the student attempts the task again in the clinical skills laboratory environment, some of this knowledge from the VR experience has been internalised as a schema for the task [56] . Although the considerations and factors removed in the VR environment are now reintroduced, an automation and accommodation of the prior experience, results in an overall cognitive load that is maintained at a reduced level. This permits the learner to direct their focus to the new factors without needing to expend limited cognitive resource on considerations that have already been addressed during the VR simulation. These two experiences then combine when undertaking the definitive procedure providing the student with increased available cognitive resource to focus on the patient and wider clinical considerations. 75% of participants so strongly felt that the two simulation modalities were complementary, that even when prompted, they would not suggest reducing the approach to the use of just one modality.

Conclusion

This paper reports the early findings of an intervention that seeks to improve dental students' confidence through the use of patient-specific VR exercises and 3D printed models. These provided an incremental learning experience for an operative clinical procedure, prior to treatment of the live patient. Early results suggest this is a positive experience for the students. These interventions may provide a valuable contribution to student confidence and preparedness. Participants felt that this preparedness allowed them to pay more attention to other factors leading to a better patient experience with improved communication and efficiency in the provision of the treatment.

These early findings are very promising and further studies might explore the manner in which the simulation sessions are delivered, the role of emerging technologies and an assessment of how an increase in confidence correlates with a matching improvement in performance.

Finally, the findings suggest that the complementary use of patient-specific VR and 3D printed models (supported with self-reflection and tutor feedback) is feasible, has high levels of acceptability within the study group and has the potential to provide effective learning and teaching that may contribute to easing the transition from preclinical to clinical operative practice. Therefore, this approach could be a valuable addition to a dental educator's toolbox. This is a promising first step in utilising VR and clinical skills laboratory-based simulation to bridge the gap between preclinical and clinical environments, although further research should be carried out with a greater number of participants to assess the impact of these technologies on student learning and patient care.

References

1. Field JC, Cowpe JG, Walmsley AD. The Graduating European Dentist: A New Undergraduate Curriculum Framework. *European Journal of Dental Education*. 2017;21(S1):2-10. doi:10.1111/eje.12307
2. (GDC) GDC. Preparing for practice: Dental team learning outcomes for registration. 2015. Accessed February 28, 2019.
3. Fugill M. Defining the purpose of phantom head. *European Journal of Dental Education*. 2013;17(1):e1-e4. doi:https://doi.org/10.1111/eje.12008
4. Serrano CM, Botelho MG, Wesselink PR, Vervoorn JM. Challenges in the transition to clinical training in dentistry: An ADEE special interest group initial report. *Eur J Dent Educ*. Aug 2018;22(3):e451-e457. doi:10.1111/eje.12324
5. Gilmour AS, Welply A, Cowpe JG, Bullock AD, Jones RJ. The undergraduate preparation of dentists: Confidence levels of final year dental students at the School of Dentistry in Cardiff. *Br Dent J*. Sep 23 2016;221(6):349-54. doi:10.1038/sj.bdj.2016.686
6. Ali K, Slade A, Kay E, Zahra D, Tredwin C. Preparedness of undergraduate dental students in the United Kingdom: a national study. *British Dental Journal*. 2017/03/01 2017;222(6):472-477. doi:10.1038/sj.bdj.2017.272
7. Rajan S, Chen HY, Chen JJ, et al. Final year dental students' self-assessed confidence in general dentistry. *European Journal of Dental Education*. 2020;24(2):233-242. doi:10.1111/eje.12489
8. Crooks D, Carpio B, Brown B, Black M, O'Mara L, Noesgaard C. Development of professional confidence by post diploma baccalaureate nursing students. *Nurse Educ Pract*. Nov 2005;5(6):360-7. doi:10.1016/j.nepr.2005.05.007
9. Morgan PJ, Cleave-Hogg D. Comparison between medical students' experience, confidence and competence. *Med Educ*. Jun 2002;36(6):534-9. doi:10.1046/j.1365-2923.2002.01228.x
10. Fine P, Leung A, Bentall C, Louca C. The impact of confidence on clinical dental practice. *European Journal of Dental Education*. 2019;23(2):159-167. doi:10.1111/eje.12415
11. Van Hell EA, Kuks JBM, Schönrock-Adema J, Van Lohuizen MT, Cohen-Schotanus J. Transition to clinical training: influence of pre-clinical knowledge and skills, and consequences for clinical performance. *Medical Education*. 2008;42(8):830-837. doi:10.1111/j.1365-2923.2008.03106.x
12. Pyle MA. New models of dental education and curricular change: their potential impact on dental education. *J Dent Educ*. Jan 2012;76(1):89-97.

13. Field J, Stone S, Orsini C, et al. Curriculum content and assessment of pre-clinical dental skills: A survey of undergraduate dental education in Europe. *Eur J Dent Educ*. May 2018;22(2):122-127. doi:10.1111/eje.12276
14. Alzahem AM, van der Molen HT, Alaujan AH, Schmidt HG, Zamakhshary MH. Stress amongst dental students: a systematic review. *Eur J Dent Educ*. Feb 2011;15(1):8-18. doi:10.1111/j.1600-0579.2010.00640.x
15. Ersan N, Dölekoğlu S, Fişekçioğlu E, İlgüy M, Oktay İ. Perceived sources and levels of stress, general self-efficacy and coping strategies in preclinical dental students. *Psychol Health Med*. Jun 2018;23(5):567-577. doi:10.1080/13548506.2017.1384844
16. Ericsson KA. Deliberate practice and the acquisition and maintenance of expert performance in medicine and related domains. *Acad Med*. Oct 2004;79(10 Suppl):S70-81. doi:10.1097/00001888-200410001-00022
17. Vincent M, Joseph D, Amory C, et al. Contribution of Haptic Simulation to Analogic Training Environment in Restorative Dentistry. *Journal of Dental Education*. 2020;84(3):367-376. doi:10.21815/jde.019.187
18. Serrano CM, Wesselink PR, Vervoorn JM. First experiences with patient-centered training in virtual reality. *Journal of Dental Education*. 2020;84(5):607-614. doi:10.1002/jdd.12037
19. Towers A, Field J, Stokes C, Maddock S, Martin N. A scoping review of the use and application of virtual reality in pre-clinical dental education. *Br Dent J*. Mar 2019;226(5):358-366. doi:10.1038/s41415-019-0041-0
20. Wang D, Li T, Zhang Y, Hou J. Survey on multisensory feedback virtual reality dental training systems. *European Journal of Dental Education*. 2016;20(4):248-260. doi:10.1111/eje.12173
21. Kroger E, Dekiff M, Dirksen D. 3D printed simulation models based on real patient situations for hands-on practice. *Eur J Dent Educ*. Nov 2017;21(4):e119-e125. doi:10.1111/eje.12229
22. Reymus M, Fotiadou C, Kessler A, Heck K, Hickel R, Diegritz C. 3D printed replicas for endodontic education. *Int Endod J*. Jan 2019;52(1):123-130. doi:10.1111/iej.12964
23. Seifert LB, Schnurr B, Herrera-Vizcaino C, et al. 3D-printed patient individualised models vs cadaveric models in an undergraduate oral and maxillofacial surgery curriculum: Comparison of student's perceptions. *European Journal of Dental Education*. n/a(n/a)doi:10.1111/eje.12522
24. Höhne C, Schwarzbauer R, Schmitter M. Introduction of a new teaching concept for crown preparation with 3D printed teeth. *European Journal of Dental Education*. 2020;24(3):526-534. doi:10.1111/eje.12532
25. Höhne C, Dickhaut N, Schmitter M. Introduction of a new teaching concept for dentin post preparation with 3D printed teeth. *European Journal of Dental Education*. 2020;24(3):499-506. doi:10.1111/eje.12528
26. Al-Saud LM, Mushtaq F, Allsop MJ, et al. Feedback and motor skill acquisition using a haptic dental simulator. *Eur J Dent Educ*. Nov 2017;21(4):240-247. doi:10.1111/eje.12214
27. de Boer IR, Bakker DR, Serrano CM, Koopman P, Wesselink PR, Vervoorn JM. Innovation in dental education: The "On-the-Fly" approach to simultaneous development, implementation and evidence collection. *European Journal of Dental Education*. 2018;22(4):215-222. doi:10.1111/eje.12331
28. Berelson B. *Content analysis in communication research*. Content analysis in communication research. Free Press; 1952:220-220.

29. Burnard P, Gill P, Stewart K, Treasure E, Chadwick B. Analysing and presenting qualitative data. *British Dental Journal*. 2008/04/01 2008;204(8):429-432. doi:10.1038/sj.bdj.2008.292
30. Constructing Grounded Theory: A practical guide through qualitative analysis Kathy Charmaz Constructing Grounded Theory: A practical guide through qualitative analysis Sage 224 £19.99 0761973532 0761973532 [Formula: see text]. *Nurse Res*. Jul 1 2006;13(4):84. doi:10.7748/nr.13.4.84.s4
31. Braun V, Clarke V. Using thematic analysis in psychology. *Qualitative Research in Psychology*. 2006/01/01 2006;3(2):77-101. doi:10.1191/1478088706qp063oa
32. Bengtsson M. How to plan and perform a qualitative study using content analysis. *NursingPlus Open*. 2016/01/01/ 2016;2:8-14. doi:https://doi.org/10.1016/j.npls.2016.01.001
33. Banerjee A, Watson TF. *Pickard's Guide to Minimally Invasive Operative Dentistry*. Oxford University Press; 2015.
34. Field J. *Pre-Clinical Dental Skills at a Glance*. Wiley; 2015.
35. Tse B, Harwin W, Barrow A, Quinn B, San Diego J, Cox M. Design and Development of a Haptic Dental Training System - hapTEL. Springer Berlin Heidelberg; 2010:101-108.
36. Wang D, Zhao S, Li T, Zhang Y, Wang X. Preliminary evaluation of a virtual reality dental simulation system on drilling operation. *Bio-medical materials and engineering*. 2015;26 Suppl 1:S747-56.
37. Konukseven EI, Önder ME, Mumcuoglu E, Kisnisci RS. Development of a Visio-Haptic Integrated Dental Training Simulation System. *Journal of Dental Education*. 2010;74(8):880-891. doi:10.1002/j.0022-0337.2010.74.8.tb04945.x
38. Weidmann SM, Weatherell JA, Hamm SM. Variations of enamel density in sections of human teeth. *Archives of Oral Biology*. 1967/01/01/ 1967;12(1):85-97. doi:https://doi.org/10.1016/0003-9969(67)90145-8
39. Wages R, Grünvogel SM, Grützmacher B. How Realistic is Realism? Considerations on the Aesthetics of Computer Games. Springer Berlin Heidelberg; 2004:216-225.
40. Larson EL, Patel SJ, Evans D, Saiman L. Feedback as a strategy to change behaviour: the devil is in the details. *Journal of evaluation in clinical practice*. 2013;19(2):230-234. doi:10.1111/j.1365-2753.2011.01801.x
41. Guadagnoli M, Holcomb W, Davis M. The efficacy of video feedback for learning the golf swing. *J Sports Sci*. Aug 2002;20(8):615-22. doi:10.1080/026404102320183176
42. Xia P, Lopes AM, Restivo MT. Virtual reality and haptics for dental surgery: a personal review. *The Visual Computer*. 2013/05/01 2013;29(5):433-447. doi:10.1007/s00371-012-0748-2
43. Ruthenbeck GS, Reynolds KJ. Virtual reality for medical training: the state-of-the-art. *Journal of Simulation*. 2015/02/01 2015;9(1):16-26. doi:10.1057/jos.2014.14
44. Roy E, Bakr MM, George R. The need for virtual reality simulators in dental education: A review. *The Saudi Dental Journal*. 2017/04/01/ 2017;29(2):41-47. doi:https://doi.org/10.1016/j.sdentj.2017.02.001
45. Dixon J, Towers A, Martin N, Field J. Re-defining the virtual reality dental simulator: Demonstrating concurrent validity of clinically relevant assessment and feedback. *European Journal of Dental Education*. 2020;n/a(n/a)doi:10.1111/eje.12581
46. Dehmer JJ, Amos KD, Farrell TM, Meyer AA, Newton WP, Meyers MO. Competence and confidence with basic procedural skills: the experience and opinions of fourth-year

medical students at a single institution. *Acad Med*. May 2013;88(5):682-7. doi:10.1097/ACM.0b013e31828b0007
47. Shah D, Haisch CE, Noland SL. Case Reporting, Competence, and Confidence: A Discrepancy in the Numbers. *Journal of Surgical Education*. 2018/03/01/ 2018;75(2):304-312. doi:https://doi.org/10.1016/j.jsurg.2018.01.007
48. Brinkman DJ, Tichelaar J, van Agtmael MA, de Vries TPGM, Richir MC. Self-reported confidence in prescribing skills correlates poorly with assessed competence in fourth-year medical students. *The Journal of Clinical Pharmacology*. 2015;55(7):825-830. doi:10.1002/jcph.474
49. Eriksson AL, Wallerstedt SM. Developing confidence in basic prescribing skills during medical school: a longitudinal questionnaire study investigating the effects of a modified clinical pharmacology course. *Eur J Clin Pharmacol*. Oct 2018;74(10):1343-1349. doi:10.1007/s00228-018-2508-3
50. Clanton J, Gardner A, Cheung M, Mellert L, Evancho-Chapman M, George RL. The relationship between confidence and competence in the development of surgical skills. *J Surg Educ*. May-Jun 2014;71(3):405-12. doi:10.1016/j.jsurg.2013.08.009
51. Crooks CV, Burleigh D, Snowshoe A, Lapp A, Hughes R, Sisco A. A case study of culturally relevant school-based programming for First Nations youth: improved relationships, confidence and leadership, and school success. *Advances in School Mental Health Promotion*. 2015/10/02 2015;8(4):216-230. doi:10.1080/1754730X.2015.1064775
52. Walker MP, Brakefield T, Morgan A, Hobson JA, Stickgold R. Practice with Sleep Makes Perfect: Sleep-Dependent Motor Skill Learning. *Neuron*. 2002/07/03/ 2002;35(1):205-211. doi:https://doi.org/10.1016/S0896-6273(02)00746-8
53. Fischer S, Hallschmid M, Elsner AL, Born J. Sleep forms memory for finger skills. *Proc Natl Acad Sci U S A*. Sep 3 2002;99(18):11987-91. doi:10.1073/pnas.182178199
54. General Dental Council. Preparing for practice: Dental team learning outcomes for registration. 2015. Accessed 3rd April 2020.
55. Sweller J. Cognitive Load During Problem Solving: Effects on Learning. *Cognitive Science*. 1988;12(2):257-285. doi:10.1207/s15516709cog1202_4
56. van Merriënboer JJ, Sweller J. Cognitive load theory in health professional education: design principles and strategies. *Med Educ*. Jan 2010;44(1):85-93. doi:10.1111/j.1365-2923.2009.03498.x

Code	**Groundedness**	**Groundedness as a percentage of participants**
Importance of the educator’s presence	7	88%
Student felt they were more efficient during the clinical procedure	7	88%

Student felt more confident when undertaking the clinical procedure	6	75%
Improved patient confidence/satisfaction	6	75%
The VR and clinical skills laboratory simulation are complementary	6	75%
Student felt it was worth the time invested	6	75%
VR was useful for establishing an ergonomic working position	6	75%
Clinical skills laboratory simulation was most realistic	6	75%
3D Printed model had an acceptable hardness	6	75%
The use of a patient specific model was essential	5	63%
Visual and quantitative assessment on VR was useful	5	63%
Hardness of the tooth in VR was not realistic	5	63%
VR was useful for planning the clinical procedure	5	63%
VR allows you to “play” with different techniques	4	50%
VR technology gives an initially challenging learning curve	4	50%
Difficult to distinguish between hard and soft tissue with the 3D printed model	4	50%
Clinical skills laboratory simulation enables students to anticipate clinical challenges	3	38%
3D printed models were very useful	3	38%
Fused contact point on 3D printed model presented issues	3	38%

Table 1: Content analysis of responses

Theme	**Selected participant quotes**
The value of virtual reality dental simulators	*"Good for achieving an overall vision of what I was trying to do and improving confidence"* *"It was good to practice in VR before going and doing it on the model – you could run through the process and try different techniques"* *"Using VR for this project was really beneficial because it allows you to do quite a lot of planning prior to the actual restorative work."* *"It was useful to look at the occlusal morphology in VR, confirm where I was going to place my depth grooves and understand the different planes of the tooth. This made practise with the 3D printed models in the clinical skills laboratory much more streamlined and more efficient than I would have done without having done the VR simulation first"* *"Posture-wise it was much, much better - this makes you sit straight"*
The value of clinical skills laboratory simulation with 3D printed models	*"When I performed the real clinical procedure, I felt that the 3D printed model was very beneficial to me because I knew where the positions I needed to concentrate on and what the positions I found difficult in the clinical skills laboratory"* *"To have it after the VR simulation was a good idea because I knew what I was trying to achieve"* *"Having the opportunity to prepare the tooth that I was going to prepare on clinic meant that I was able to get tutor feedback prior to doing the preparation. Also, I was able to take the preparation on the model home to study and prepare even more"*

	"Because you're working in an oral cavity and using the same instruments as you will with the patient it's more realistic" *"Normally in the skills laboratory the teeth are perfect and that's just not the case when providing this treatment for real patients. Whilst it's important to learn to do conservative preparations on a sound tooth it's very different on a patient who actually needs the crown"*
The value of educator engagement	*"It was very beneficial to have tutor feedback"* *"If I was here on my own I wouldn't learn or benefit as much because it would be just me here on my own with my limited knowledge"* *"You can understand it a lot better if you are getting feedback on something you've actually done as opposed to a tutor telling you before you do something on a patient that these are the problem areas where you might find things a bit more difficult."* *"There are areas where you might not know you've made a mistake so it's good to have those pointed out"* *"The tutor feedback was the main draw for me. When you go on to clinic you feel much more confident"*
The impact on the clinical procedure and the patient	*"Good to take the 3D model to show the patient and reassure them - they know we're still learning so it's good to show them"* *"It showed we were putting time and effort in to the patient and it was specific to them"* *"Felt more confident. I thought, I've done it before so if I just do those steps again it should go similarly"* *"It made the appointment where I was doing the preparation more efficient because I understood the process and knew what to do"*

	"You've already done the preparation, you already know what to do with the tooth, and all you have to do on the day is focus on the patient" *"I really feel it helped put me at ease because it was quite a difficult preparation… on the day I knew exactly what I had in mind I knew how I was going to do it"*
The virtual reality and clinical skills laboratory balance	*"I was more efficient in the skills laboratory because I'd had time in the VR simulation suite… and because it wasn't the same day, I had a day to go away and process what I'd learned and come back to it so it was helpful"* *"I actually enjoyed the process, both the laboratory component and the virtual reality complemented each other quite well"* *"Working with VR helped smooth things out before I went on to the 3D printed model. I think I would have made more mistakes on the model and taken longer. I don't think VR could be used on its own necessarily but VR then the 3D printed model is quite a good way of doing it"* *"I got a real understanding of what I was going to do, I had a good image of the actual tooth, then going to skills laboratory I knew exactly what I was going to do - VR changed how I would have tackled the procedure"* *"I think that both are very useful and have their part to play. In regard to the actual preparation the skills laboratory is more useful but for the planning and to improve the time spent in the skills laboratory you need to have the VR as well."* *"The clinical skills laboratory is more realistic but the VR will get you into better habits."*

Table 2: The themes established through the thematic analysis and associated student quotes.

Figure 1: Summary of model acquisition and preparation process

Figure 2: Virteasy Dental Skills Simulator

Figure 3: 3D Printed teeth mounted in a phantom head