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A Scoring System for Assessing Learning Progression of Dental Students' Clinical Skills Using Haptic Virtual Workstations

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Abstract: The aim of this study was to develop and test a scoring system to assess the learning progression of novice dental students using haptic virtual workstations. For the study, 101 first-year dental students at a UK dental school conducted one practice task (task 1) and four simulated cavity removal tasks (tasks 2-5) of increasing difficulty over two laboratory sessions in 2015. Performance data on the students' attempts were recorded as haptic technology-enhanced learning (hapTEL) log-files showing the percentage of caries, healthy tissue, and pulp removed. On-screen results were photographed and submitted by the students to the tutors. A scoring system named the Accuracy of Caries Excavation (ACE) score was devised to score these results and achieve an even distribution of scores and a calculated combined score. A total of 127 individual logged attempts by 80% of the students over sessions 1 and 2 were recorded and submitted to the tutors. The mean ACE scores for both sessions for tasks 2 through 5 were 9.2, 11.6, 6.4, and 4.9, respectively; for Session 2 (tasks 3-5), scores were 12.4, 6.7, and 5.0, respectively ($p<0.001$). The average performance on task 3, which was attempted in similar numbers during both sessions, improved from the first to the second session (8.14 vs. 12.38; $p=0.009$). Using the HapTEL system in a first-year BDS curriculum improved the students' performance of simulated cavity preparation after practicing over two sessions. Use of the ACE scoring system enabled tutors to make consistent assessments across a large student cohort and provided an objective method of formative assessment.

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There have been previous studies on the uses of virtual dental simulators using haptics to enhance the teaching of dental students.[1-4] However, very few of these involved assessing large cohorts of students' improvement in performance, which can reveal their learning progression over time. A very recent review by Roy et al. found that virtual dental systems were still infrequently used in most dental programs.[4]

Standard dental curricula include preclinical use of phantom-head manikins with a typodont model of the oral cavity containing plastic or human-extracted teeth to allow students to develop their procedural skills before treating actual patients.[5-7] Although these teaching resources have been found effective in improving students' preparation skills, there are cost and storage implications.[5] Clinical teaching with limited teaching resources can provoke anxiety in some novice dental students.[6] Traditionally, such practice sessions are supervised by clinical tutors, providing oral feedback to the students. The effectiveness of such sessions depends on the teacher's abilities and the number of tutors available to provide frequent feedback to assess students' learning progression.[8] Virtual reality systems (VRS) provide benefits to traditional simulation teaching such as providing unlimited virtual teeth, immediate objective individual feedback, and unlimited user practice while reliably tracking students' progress.[9,10]

Popular dental VRS systems include the Virtual Reality Dental Training Systems (VRDTS) for caries removal and periodontium measurement, the Iowa

Dental Surgical Simulator (IDSS) for caries detection, PerioSim for subgingival calculus detection, and Dental Trainer for cavity preparation.[4] However, many of the previous evaluations of such systems have been short-term,[5] involved small student cohorts,[9] were limited to measuring attitudes rather than impact on learning gains,[9,11] and rarely involved the integrated use of virtual simulators over a sustained period.[4] Some educators have been positive about the perceived educational value of VRS systems,[8,11-13] whereas other studies found that students felt they did not hold an advantage over traditional teaching methods.[4,14] Such conclusions about VRS system efficacy based only on students' perceptions have limited value because they do not progressively record the impact of the activity on students' learning of specific clinical skills. The randomized controlled trials investigating the efficacy directly are limited,[15,16] although a smaller study in which VRS was extensively incorporated into the curriculum found that students with access to VRS needed less preparation time to achieve similar summative exam results as those without VRS.[17] Quinn et al. found a significant difference in learning gains between a VRS group and a traditional group for outline form, depth, and smoothness but not for retention or cavity margin angulation.[18]

Assessing clinical skills during training can also be subjective. Moorthy et al. and Yin et al. argued that, without objective feedback, improving performance is difficult, so more use should be made of validated methods such as checklists, rating scales, and dexterity analysis systems.[19,20] Other than the latter study, however, the literature does not report on formative feedback using scoring systems for virtual reality simulators. The varied conclusions from these showed that more research and assessment tools were needed to measure the impact on students' learning and their learning progression of specific clinical skills when using VRS in the formal dental curriculum.

The aim of this study was to develop and test a scoring system to assess the learning progression of novice dental students using haptic virtual workstations. To achieve this aim, the objectives were to assess the performance of a cohort of dental students using the Haptic Technology Enhanced Learning (hapTEL) system in their curriculum; measure how their performance progressed from the first to the second sessions; analyze the cavity preparation results recorded through log-files of each student's records; and create and use a scoring system as a measure of overall performance, thereby to examine factors that influenced performance amongst this student cohort.

Materials and Methods

Ethical approval for the one-year study was granted by King's College London in June 2014 (Ref. number: BDM/13/14-96) to evaluate the impact of the hapTEL system on students' learning. The virtual dental system was used with all 101 BDS Year 1 students from January to March 2015 as an integral part of their Year 1 curriculum to teach them basic clinical cavity preparation skills. These were novice students, five months into their course, who had never used a dental handpiece for cavity preparation and had no previous training in either the use of the traditional phantom head workstation nor the virtual dental workstation.

The hapTEL system used by the students was collaboratively developed in the UK over a period of four years (2008-11).[15,16,21-23] HapTEL replicates the feeling of performing cavity preparation and caries removal and consists of a haptically enabled modified dental drill providing realistic force-feedback to the operator during use in the virtual clinical environment. The system includes a set of teeth in a jaw and the dental drill, which are displayed on a 3D dual-screen system viewed by the operator using 3D glasses (Figure 1). A camera that tracks the movement of the student's head provides collocation of the image with the student's position, so that the student can move his or her head around the mouth to get the best view as in real life. A virtual drill shown on the screen is operated by the haptically enabled drill controlled by the student. Drill power is controlled using foot pedals.

Learners can select from a choice of scenarios and complexities, which generally involve a decayed cavity lesion requiring excavation. The system is set up to log raw data on each attempt and feeds back information such as the amount of decay, enamel, dentine, and pulp removed at the end of the attempt. Users can replay their attempts on the screen to assess and learn from their performance.

Before using hapTEL, the students were shown a video with information about personal protective equipment, how to sit ergonomically, how to hold the virtual handpiece and use the finger rest, and the functions of the workstation. These first-year students had not received any clinical training nor yet been

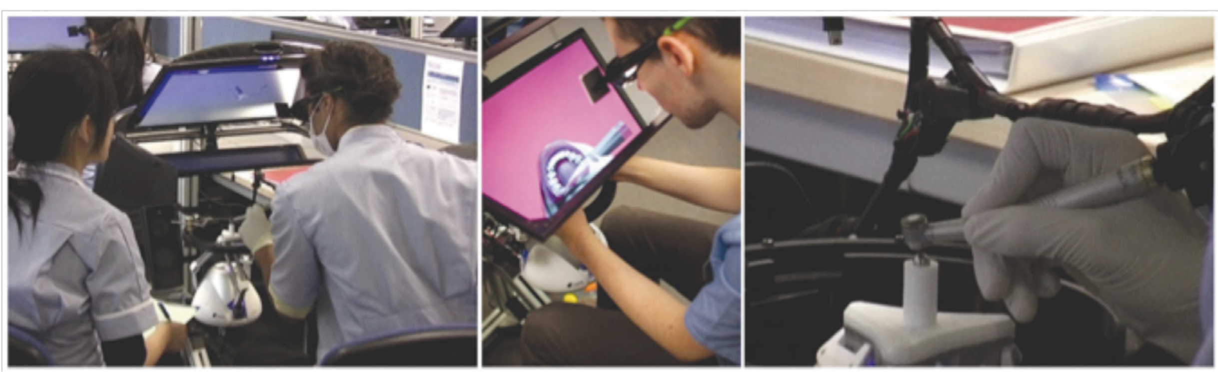


Figure 1. Virtual hapTEL simulator (top), with (bottom, left to right) student pair working at the device; view into the virtual mouth; and dental handpiece connected to the device

taught about the biological basis of caries removal. The focus of the virtual laboratory sessions at this stage was mainly on mechanical aspects of developing students' fine and gross motor skills and hand-eye coordination in a virtual dental context and familiarizing themselves with the caries removal tasks in a dental curriculum.

Following orientation, the students were split into 12 tutor-groups of nine to 12 students each. They conducted cavity preparation in two one-hour supervised teaching sessions using the hapTEL VRS system. Students were given an introduction to the hapTEL system, then allocated a partner to share a hapTEL workstation. If there were odd numbers of students, one student would either work on his or her own with help from one of the tutors or join a two-student group to make a threesome. The latter option meant that there was less time for the three students to take turns to complete all the tasks.

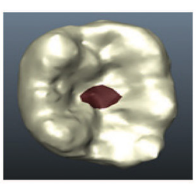
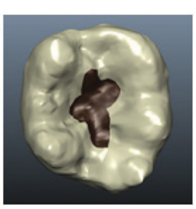
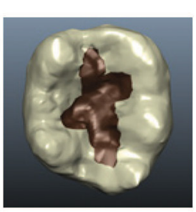
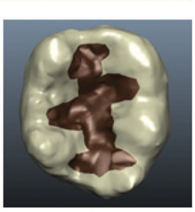
The sessions were two to three weeks apart. One student operated the hapTEL simulator; the other acted as the nurse, operating the vertical control screen to select the handpiece, speed of drill, and specific task and deciding on whether to use loops (to magnify the tooth up to six times). Five tasks were provided for these sessions.

Table 1 shows diagrammatically and numerically the shape and size of the carious lesions for the practical tasks undertaken by the students. The % area is the percentage area of the occlusal surface taken up by the carious lesion The practice task 1 involved operating on a "floating tooth," which was a single non-carious virtual tooth not located in a jaw (similar to the plastic or discarded human tooth held by the student in the phantom-head laboratory). This tooth could be operated on and oriented by the students to familiarize themselves with the VRS. They were not required to record their performance on this task. The remaining tasks involved the need to excavate carious teeth of increasing difficulty. Task 2 involved operating on a single tooth on the screen (floating tooth) with a small carious lesion. Tasks 3-5 involved operating on a mandibular first molar situated in the lower jaw: with a small carious lesion (task 3), a carious lesion already in the dentine (task 4), and a carious lesion already in the dentine and only 0.39 mm from the pulp (task 5). The distances from the pulp and other tooth dimension for the virtual teeth were simulated to coincide with the manufactured plastic teeth distances as used in a larger previous study.[14]

Students were expected to attempt the less difficult tasks (1 and 2) during the first session and the more difficult tasks (3, 4, and 5) during the second session, although some students completed task 3 during the first session. They were advised to attempt the same task several times within the timetabled slot for the session. Partners were asked to split the session time equally and for each to attempt every task at least once.

The hapTEL system is configured to anonymously log the percentages of tissue (enamel, caries, dentine, and pulp) removed by the student for each attempt, recording whether pulp exposure occurred

Table 1. Details of simulated carious lesion practical tasks stored in hapTEL system

Task	Image	Shortest Distance Between Two Closest Points of Carious and Pulpal Volumes	% Area of Occlusal Surface Taken Up by Carious Lesion	Volume of Carious Lesion as % of Entire Tooth
1			No carious lesion	
2		1.17 mm	5.3%	0.6%
3		1.09 mm	11.1%	0.8%
4		0.67 mm	18.9%	2.7%
5		0.39 mm	28.0%	3.6%

as well as the time (in seconds) delay to first drill contact and the time (in seconds) spent drilling. Students were asked to photograph their results on the screen and submit them subsequently to the tutors.

A computer program was created to extract the data from log-files and create a spreadsheet containing the data of each of the students using the hapTEL system. The spreadsheet was organized and prepared for importing into SPSS (IBM Statistics, version 23.0 for Windows) for analysis.

Attempts were excluded when the time spent working on the tooth was less than ten seconds or where there was <0.5% removal of caries, dentine, and enamel as that was not considered a serious attempt. Task 1 attempt data were not used in the analyses as the task was a simple practice tooth that did not involve the need to excavate carious lesions.

In order to obtain an objective measurement of clinical skills performance, a scoring system of task attempt performance was devised. Task difficulty was then examined by comparing performance scores using the analysis of variance (ANOVA) test. Students' performance on task 3 (attempted in both sessions by many students) between sessions 1 and 2 were compared using a one-way ANOVA test. The effect of delay to first contact and time (in seconds) spent working on the tooth on performance was analyzed with Spearman's rank correlation coefficient.

Results

The variation and uncertainties in some of the data recorded did not provide consistent evidence of improvement for all students from session 1 to 2 across all tasks with the exception of task 3. This was because, although out of the total cohort of 101 students, 98 (97%) students attended session 1 and 94 (93%) attended session 2, each student worked at a different pace. Some students who learnt very quickly how to use the system moved on to task 2 then 3 in session 1, while others could only attempt tasks 1 and 2 in the first session. Out of the 98 students completing the tasks in session 1 and 94 in session 2, the number of attempts recorded and submitted for assessment by the students for tasks 2, 3, 4, and 5 for sessions 1/2 were 42/1, 7/29, 3/23, and 1/21. The median delay before first contact was 25 seconds. The median time spent working on the tooth was 131 seconds. These numbers differed from the total number of students actually attending the sessions because some students only recorded their performances for both partners rather than individually and some students forgot to submit their scores subsequently to the tutor.

The previous scoring system used by the faculty for the phantom-head laboratory (2008-11) involved assessing the angle of entry, the hold of the instruments, the area of caries remaining from both the cavity wall and the cavity floor, the avoiding of pulp exposure, and the conservation of healthy tooth structure.[24] For this study, we developed a similar scoring system for hapTEL cavity preparation tasks named the hapTEL Accuracy of Caries Excavation (ACE) score) (Table 2) to assess the VRS data recorded by the log-files.

The three dimensions included in the ACE score were caries removed, healthy tissue remaining (enamel and dentine), and pulp remaining (less than 100% was deemed an exposed pulp). The removal of enamel and dentine healthy tissue was combined into one score (maximum of 5). Since there was approximately double the amount of dentine than enamel in the tooth and the software currently produces measures for proportions remaining, not absolute mass remaining, we decided to score each percentage point of dentine to represent double the area of a percentage point of enamel. Scoring thresholds were established for each of these dimensions. Any pulp exposure was considered an undesirable outcome that should incur a large penalty.

The maximum scores possible for each of the three categories were based on an ideal performance desired in a real life scenario. The thresholds used to score caries removed, healthy tissue remaining, and pulp remaining were chosen to achieve a good distribution of scores. The sum of the three scores gave the final ACE score. The maximum possible ACE score was 18. Figure 2 shows the distribution of all the students' ACE scores. No attempts received scores of 0, 17, or 18. The distribution of ACE scores was not even: for example, 17 students scored 14, compared with three students scoring 1 overall. The

Table 2. New hapTEL Accuracy of Caries Excavation (ACE) scoring system

Caries Removal	Healthy Tissue Remaining	Pulp Remaining
5: 100%	5: 100%	8: 100%
4: 95%-99%	4: 98%-99%	4: 99%
3: 90%-94%	3: 97%	3: 98%
2: 75%-89%	2: 95%-96%	2: 97%
1: 50%-74%	1: 90%-94%	1: 96%
0: <50%	0: <90%	0: <96%

Note: ACE Score = Caries Removal Score + Healthy Tissue Remaining Score + Pulp Remaining Score. Maximum ACE score possible was 18.

mean ACE score for all tasks was 8.5. Mean and median scores for all tasks are shown in Table 3.

More difficult tasks were associated with lower ACE scores. The ACE scores achieved and time spent removing caries during tasks in session 2 were analyzed. The mean ACE scores for tasks 3, 4, and 5 were 12.4, 6.7, and 5.0, respectively (p<0.001). The mean times spent working on the tooth were 168.3, 195.4, and 168.0 seconds, respectively, but these differences were not statistically significant (p=0.531).

Students performed better in session 2. Task 3 uniquely had an adequate number of attempts in both sessions 1 and 2 to perform a low-powered comparison of the mean ACE score and to show any learning progression. A comparison (Figure 3) showed attempts in session 2 had a higher ACE score (8.14 vs. 12.38, p=0.009) than in session 1.

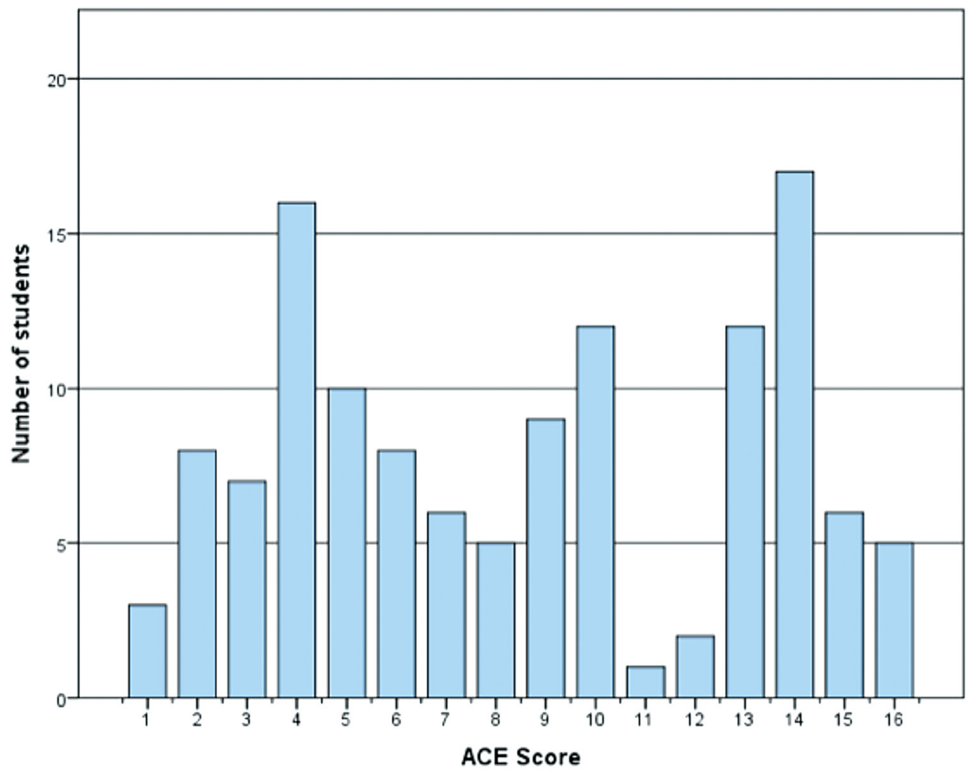


Figure 2. Distribution of overall Accuracy of Caries Excavation (ACE) scores (n=127 attempts)

Table 3. Accuracy of Caries Excavation (ACE) scores by task

Score		All Tasks	Task 2	Task 3	Task 4	Task 5
ACE score	Mean	8.5	9.2	11.6	6.4	4.9
	Median	9.0	10.0	13.0	5.5	4.0
	Standard deviation	4.5	4.8	3.6	3.4	2.4
Caries score	Mean	2.0	1.4	2.3	2.2	2.1
	Median	2.0	1.0	2.0	2.0	2.0
	Standard deviation	4.5	4.8	1.2	0.8	0.8
Healthy tissue score	Mean	2.8	3.3	3.4	2.1	1.5
	Median	3.0	3.0	3.0	2.0	1.0
	Standard deviation	1.5	1.5	1.3	1.4	0.9
Pulp exposure score	Mean	3.8	4.4	5.8	2.1	1.2
	Median	4.0	4.0	8.0	1.5	0.0
	Standard deviation	3.3	3.4	2.7	2.4	2.0

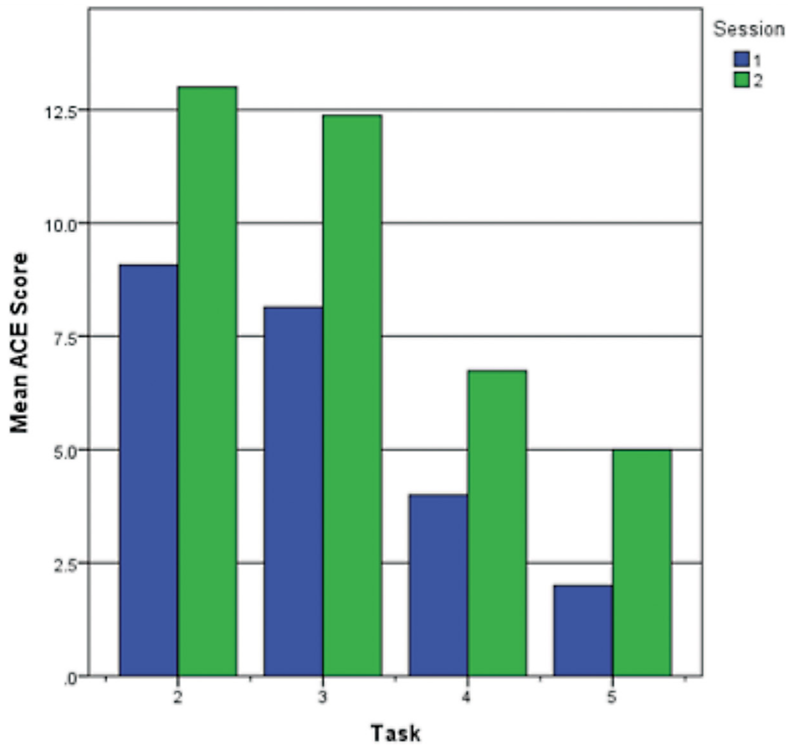


Figure 3. Comparison of mean Accuracy of Caries Excavation (ACE) scores between sessions 1 and 2 for tasks 2, 3, 4, and 5

Students who delayed first contact performed better. The ACE scoring system was applied to all attempts in tasks 2-5, and an analysis was performed to examine correlation with delay to first contact and time spent working on the tooth. A higher delay to first contact was associated with a better score (p=0.001, coefficient=0.304, delay measured in seconds), while time spent working on the tooth was not (p=0.090). To examine this effect further, an analysis of each aspect of the ACE score was performed to see which aspect of the performance improved. Delaying first contact had no statistically significant impact on the caries removal score (p=0.832) but a positive impact on the healthy tissue remaining score (p<0.001, coefficient=0.331) and pulp exposure score (p<0.001, coefficient=0.524).

Discussion

The hapTEL system used in this study forms a core part of the Year 1 dental undergraduate curriculum to practice caries removal. Assessor subjectivity and inconsistency identified as significant problems in previous studies could be solved by providing instant objective performance feedback through using VRS systems instead.[25,26]

In this study, we found that hapTEL gave students a detailed breakdown of their attempt to highlight the areas for improvement. A review of e-learning by Arevalo et al. concluded that the students learned from the feedback hapTEL produced, which improved clinical skill performance when working on the tooth at the enamel dentine junction.[26] The quantitative nature of the feedback allows students to monitor their progress objectively and institutions to assess their students for formative or summative exams. Previous studies of the hapTEL system involving qualitative video observations and recordings of student-tutor interactions highlighted the ways in which tutors routinely invoke real life in instructional corrections and undertake to compensate for the mechanistic features of the simulator.[23] This occurred during the hapTEL sessions with one to two tutors circulating amongst the students, reminding them of their educational goals and reinforcing the experience for the longer term biological aims in real patient situations. It is well established that these forms of assessment aid students' learning.[25,27] A study conducted by San Diego et al. concluded that formative assessment should be provided on a continual basis.[24] Electronic learning assessment methods are encouraged by the Higher Education

Funding Council for England (HEFCE), which concluded that e-learning benefits both students and tutors and enables easy data transfer across institutions and awarding bodies.[28]

Our study was conducted to examine the performance of students' cavity preparation skills in an undergraduate curriculum. The ACE scoring system was developed and worked well as a measure of performance for our analyses. Scoring systems are a new concept to virtual reality, in which usually the software generates analysis of performance indicators and is then interpreted by the tutor when giving feedback to the student. The potential exists to introduce further meaningful variables into the score calculation such as the angle of entry into the mouth, therefore helping students learn and practice correct habits. The more skills the system can measure and provide feedback for, the higher the educational value that can be achieved with hapTEL through self-directed learning without a supervisor. This point supports the recent findings of de Peralta et al. who showed that learning assessment that encouraged students' reflection and self-evaluation improved their competence in caries excavation of extracted teeth.[8] The results in our study showed that, after one session of practicing with hapTEL, students had a statistically significant (p=0.009) improvement in performing haptic caries removal. This was based on task 3 performance in session 1 (before practice, average ACE score=8.1) compared to session 2 (after practice, average ACE score=12.4).

Students are taught by their faculty members to plan carefully for clinical procedures, and indeed students who adopted this strategy performed better in our study. Students who delayed their first contact had higher ACE scores (p=0.001), and the magnitude of the effect was large (coefficient=0.3, delay measured in seconds). From the tutor observations, the students who took longer to start the procedure spent more time adjusting their posture, orienting the tooth and jaw for the best view of the tooth, and ensuring they were holding the handpiece correctly. Interestingly, delaying first contact was mostly associated with a reduction in the amount of healthy tissue removed and pulp exposed, not an increase in caries removal.

This study had several limitations. The discrepancy between the number of attendees and the number of recorded attempts was due to several reasons: students' forgetting to log out at the end of their turn, resulting in the system continuing to record the second student's action in the same log-file; poor time management by some students, resulting in some of them taking much longer to complete one operation and subsquently leaving less time to complete all the tasks; and about 20% of the students forgot to send in their photographed results to the tutor following the sessions.

As each attempt was anonymously recorded, with the only identifiers being the attempt date and time, it was not possible to identify the number of attempts made by individual students—only the total number made by the whole cohort. HapTEL can be configured to record individual user details, which would make it easier to determine the causes of such discrepancies in further studies. This process was done for the previous study, thereby showing the individual performance of every student, and could be done more systematically in the future.[22] Furthermore, increased insight could be gained by directly comparing a student's performance between sessions 1 and 2 if every individual user's details are recorded. Subsequent to the study reported here, every student is now required to record his or her on-screen performance data onto a record sheet during the session, therefore ensuring 100% of student attendees' results and identification of each student's individual performances. This process will enable us to repeat the analysis using the ACE scoring system with a larger, more substantial set of results, which will be reported subsequently.

The improvements in task 3 performance between sessions 1 and 2 confirmed an improvement in fine motor skills and more accurate conservative removal of caries. This finding could be due to the feedback received and improving with practice and possibly improved familiarization with the system. These results confirm a previous longitudinal study (2008-12) that measured improvement of fine and gross motor skills over a four-year period using psychometric tests of students who were already familiar with the system.[29]

Conclusion

This study found that students performed better after practicing with the VRS hapTEL system, further establishing it as a viable training tool for novice dental students. The range of features that enabled it to be incorporated easily into the undergraduate dental curriulum were comparable to some other simulators, such as enabling students to work in pairs, tutors to engage with students in the learning activity with the large screen, and providing immediate feedback and context of the learning experience. Contrary to the assessment procedures in the traditional phantom head laboratory, this VRS system provides a permanent record of each and every student's performance through the log-files. Implementation of the ACE scoring system allows the possibility for consistent assessment for any VRS system that records similar data. However, further validation with successive large cohorts of students is necessary to ensure reliable outcomes with the ACE scores for different student cohorts.

Acknowledgments

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