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Al Saud, LM, Mushtaq, F orcid.org/0000-0001-7881-1127, Allsop, MJ orcid.org/0000-0002-7399-0194 et al. (6 more authors) (2017) Feedback and motor skill acquisition using a haptic dental simulator. European Journal of Dental Education, 21 (4). pp. 240-247. ISSN 1396-5883

https://doi.org/10.1111/eje.12214

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Feedback and motor skill acquisition using a haptic dental simulator

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Article Type: Original Article

Running title: Feedback and motor learning in dentistry

Keywords: Skill acquisition, dentistry, undergraduate dental education, virtual reality, feedback, motor learning.

Conflict of Interest:

The authors declare no competing financial interests.

Acknowledgments:

We would like to thank Dr Liam Hill for his comments on an earlier draft of the manuscript.

1 Introduction

The goal of dental education is to facilitate the development of an individual to a level where they are capable of safe, effective and independent practice (1–3). This degree of competency comprises academic knowledge, clinical skills and professional attitudes - factors that define the minimum acceptable performance level for a dentist at the time of graduation. As part of this process, students must also display a high level of manual dexterity proficiency, with fine motor skills typically developed first in simulation laboratories over the course of an undergraduate degree. This emphasis on fine motor skills is particularly relevant for operative dentistry - the foundation of almost all dental specialties and the area where the majority of preclinical teaching time is dedicated (4). Thus, it is not surprising that time spent learning the motor skills required for competent practice is a core feature of the dental curriculum. The task facing dental education is how to best teach these skills to the standard required in the allocated time - a challenging and resource-demanding process.

In the last three decades, computer simulation has become widely adopted in high-risk industries where small errors can have a profound impact on safety. Demonstrable success in improving standards has come from the aviation industry - where flight simulators have contributed to drastic improvements in safety (5) - and the military (6). In healthcare, and specifically surgery, computer simulation has become increasingly prevalent as a means of training clinicians, evaluating competency and as a tool for reducing errors (7–9). Dentistry is relatively unique amongst health care specialities in that it has a long history of using simulators in training (10). Dental educators have used simulation primarily to provide a safe learning environment for students to learn fine motor skills before they treat real patients. Simulation has also been used to facilitate the transition into the dental clinic and enhance a students' preclinical experience through inclusion of a wide range of simulated patient scenarios (11).

Central to effective learning in simulation based education is the role of feedback on a learner's performance (6,12,13) - the primary focus of the present work. Substantial evidence from experimental psychology suggests that feedback modulates the rate of learning and that appropriate feedback at various stages of skill acquisition can accelerate the learning process (14–19). In motor learning, the feedback signal includes all of the sensory information available as a result of a movement (20). The majority of research indicates that motor skills can be enhanced when concurrent feedback is provided as it decreases memory demands, directs the attention of the trainee to the relevant aspects of the skill and facilitates the understanding of the underlying processes required to complete a difficult motor task (21–24). Nevertheless, some studies have shown that inappropriate feedback during motor skill acquisition may produce a dependency on this information (25) and thus interrupt the learners' intrinsic representation of the task and thereby negatively impact on long-term learning (21).

Feedback can be obtained in a multitude of ways - it can be intrinsic or extrinsic, unimodal or multimodal and can be accessed continuously (concurrent feedback) or at discrete stages of task performance (e.g. terminal feedback) (21,26). Typically, feedback is categorised as either: (a) information about the outcome of the performance, which is known as knowledge of result (KR) e.g. feedback provided by an instructor when the student has completed all or part of the dental task, such as cavity preparation (27); or (b) information about the quality of performance and movement characteristics - known as knowledge of performance (KP)- comprising information that is not available in a conventional dental training environment. The availability of KR feedback during simulated practice has been identified as one of the most important factors that leads to effective motor learning (21–24).

Virtual reality (VR) simulation technologies offer an opportunity to present on-line continuous feedback on surgical performance through presentation of visual and auditory information (28). In recent years, the introduction of haptic technology has enriched these simulators with sensory (tactile) feedback that allows trainees to feel and touch virtual objects – thereby providing information that can potentially be used to learn the parameters of a task above and beyond auditory and visual cues. Whilst this technology is relatively new to dentistry, the relationship between feedback and skill acquisition has been explored previously in other surgical disciplines.

In laparoscopic surgery simulator training, novice surgeons have shown a faster learning rate when trained with haptic feedback compared to no haptic feedback in early stages of skill acquisition (29). For novice trainees however, whilst VR feedback has shown to result in general improvements in performance in difficult endovascular skill training, skill acquisition is further accelerated through the introduction of expert instructor guided feedback (30). Similarly, the availability of instructor feedback in VR laparoscopic complex skill training has been shown to increase learning efficiency (31)- although it may not affect long-term retention of the learned skill (32).

In the dental literature, the use of VR simulators for undergraduate operative dentistry training has been shown to be effective in providing objective formative evaluation, and in enhancing skill acquisition rates (33). Additionally, learners with low visual-spatial ability seem to benefit more from simulation training than conventional training (34). The role of feedback in dental preclinical training has also been investigated in conventional (27), computer-assisted (35) and VR environments (36,37). In conventional preclinical operative training (phantom head simulators), the effect of providing continuous concurrent feedback from an instructor has been found to result in significant performance improvements relative to presentation of terminal KR feedback alone (27).

In a series of experiments, Wierinck et al. explored the role of augmented feedback from a computer-assisted simulator (DentSim^{TM}) on skill acquisition (35,38,39). The simulator allowed the student to practice dental procedures using plastic teeth and a real hand piece, while providing augmented visual computerized feedback about a student's preparation compared to an ideal standard. In one study, when only one type of feedback was provided (visual feedback from the simulator) to novice dental students, performance was enhanced temporarily during training of the manual dexterity skills, but this did not result in retention

(35). In another study, standardised expert input provided at a tutorial session before students completed a task was found to be more beneficial for retention and transfer of skill than VR feedback alone (39). Similarly, using a haptic VR simulator, Suebnukarn et al (2010) showed that providing augmented kinematic feedback about variations of movement pattern whilst performing an endodontic access preparation enhanced student performance at the early stages of skill acquisition and retention (36).

In concert, these studies suggest that: (i) VR simulator-driven feedback can be useful as a means of improving performance; (ii) multi-modal feedback methods should result in faster skill acquisition relative to VR alone; (iii) the presence of experienced instructors providing online feedback might complement VR training in the early stages of skill learning, leading to superior retention. Thus, there is growing convergent evidence to suggest that VR dental simulators could be a useful adjunct to traditional dental training methods (40–44) . Nevertheless, there is a need to directly test the usefulness of haptic dental VR simulators and empirically determine the best pedagogical environment. In a recent review, Cox et al. compared two haptic dental simulation systems and their impact on dental undergraduate students skill learning by evaluating evidence from longitudinal research findings. The review concluded that haptic simulation enhances student skills in hand-eye coordination, fine motor skill learning, and self-reflection (45).

Predicated on the existing research, the aim of the current study was to examine the contributions of feedback from: (i) a VR haptic simulator, (ii) an instructor and (iii) a combination of the two. In order to avoid confounding effects, the experiments were conducted with naïve subjects with no previous dental training. Specifically, we investigated the impact of feedback on: (a) rate of motor skill acquisition; (b) the ability to generalise the learnt skill to other tasks (skill transfer); and (c) long-term changes in learning (retention).

2 Materials and Methods

2.1 Participants

Sixty-three participants (mean age = 22.7 years, SD = 3.4 years) with no previous dental training participated voluntarily in the study following email and poster announcements at the University of Leeds in exchange for £20 remuneration. In order to ensure that the data collected on our dentistry-naïve sample could be translated to dental education, our sample included participants with a comparable age and level of education to a typical undergraduate dentistry cohort. The participants were remunerated for their time and it was made clear that payment would not be dependent on performance. Participants were randomly allocated to one of three groups. Each group (n = 21) received qualitatively different types of pedagogical feedback during dental training, described in the procedure section below. Participants completed an informed consent sheet, were fully debriefed and the study was approved by the ethics committees of the School of Psychology and School of Dentistry at the University of Leeds.

2.2 Apparatus

Participants were trained and tested on the Simodont VR haptic dental simulator (MOOG, Nieuw-Vennep, Netherlands). The simulator provides haptic force feedback with a realistic feel, based on the admittance control paradigm of the HapticMaster (46), which means that the simulator responds to force exerted by a user, leading to a sense that the user is interacting with an object of equal mass. The Simodont includes a computer screen that shows high-resolution images of teeth, and dental instruments with 3D projection when the users wear stereoscopic glasses. Underneath the screen is a physical handpiece with a virtual tip, which can be used to perform tooth preparation procedures with realistic sound rendering. The speed of the virtual hand piece in the system we used could be controlled using a real foot pedal. The simulator is supported by bespoke “Courseware” software (developed by the Academic Centre for Dentistry Amsterdam (ACTA), Amsterdam, Netherlands). This software comprises a range of manual dexterity exercises and operative dentistry procedures with levels offered at varying difficulty and captures the real-time kinematics of student performance (**Table 1**). For this study, we used the manual dexterity exercises from the Courseware package to train and test all participants to prepare basic abstract shapes using the same dental instruments (high-speed hand piece and one type of dental bur-FG856/016). We recently demonstrated that using these tasks, the Simodont is able to capture differences in varying levels of dental expertise (47).

In order to ensure equivalence in underlying motor abilities in our sample, the clinical kinematic assessment tool - (CKAT; (48)) an objective measure of motor control - was used to assess motor ability at baseline. The data processing steps and task requirements for the battery are described in more detail elsewhere (49,50).

Table 1 Kinematic performance measures provided by the Simodont

A- Target removal (%)
B- Error Scores (%) 1- Leeway bottom 2- Leeway sides 3- Container bottom 4- Container sides
C- Time elapsed (seconds)
D- Drill Time (seconds)
E- Handpiece movement (m) 1- Moved with left hand 2- Moved with right hand

2.3 Tasks

Five different geometric shapes, available in two different depths (0.4 mm and 0.8 mm) were employed in this experiment. A schematic example of one of the shapes (cylindrical) is shown in Figure 1A. Each shape consisted of three zones (Figure 1B): (i) a target zone- which must be removed by the participant; (ii) Leeway zones (side and bottom) is adherently surrounding the target zone and the participants were instructed to avoid removing as possible; and (iii) the container zones (sides and bottom) represented by a block that surrounds the abstract shape that participants were also told they must avoid during target removal. Participants were informed that the acceptable target removal percentage of all tasks in this study was 70% **(**Table 2**).**

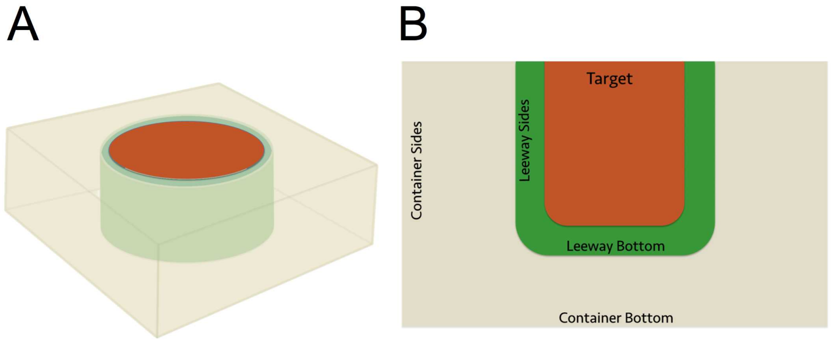

Figure 1 (A) Schematic drawing of one of the abstract shapes available in manual dexterity training section of the Simodont courseware; (B) Cross-section of the abstract shape (3 coloured zones).

2.4 Procedure

After completing the CKAT battery, participants were given a 10-minute introduction to the Simodont haptic dental simulator. This was followed by a demonstration of how to use the handpiece and the foot pedal to remove the marked orange target area of the shape (see Figure 1B) and avoid going beyond the shape boundaries. Each participant was allowed to try out the device as part of the introduction to familiarize themselves with the procedure and the required task. Next, a baseline skill (BL) assessment was conducted where participants were asked to prepare a simple abstract shape (with no feedback at all). The training phase included practice completing four exercises on two abstract shapes. During this phase, each group received a different type of feedback during training. One group (referred to as Device Feedback [DFB] from hereon in) received feedback from the Simodont only i.e. visual display of kinematic information about performance including error scores, drill time, and task completion percentage (see **Table 1**). Group 2 (Instructor Verbal

Feedback; IFB) received verbal feedback from a qualified dental instructor only, with no access to information from the device (i.e. no visual display of kinematic measures). The verbal feedback from the instructor included comments about performance (e.g. cutting the target area, holding the handpiece) in addition to answering questions about the task and the procedure. Group 3 (Instructor and Device, [IDFB]), received combined feedback from the same instructor (verbal instructions about performance) and device (visual display of kinematic information). The same instructor provided feedback to the IFB and IDFB groups.

The training phase was followed by a transfer test to examine skill generalisation. Here, all participants performed two tests on novel abstract shapes that had not been encountered during training (without feedback). The retention phase of the study consisted of post-tests performed at three-time intervals (immediate, one-week, and one-month). The exercises performed at these sessions were identical to the shape practiced during the training phase (without feedback). With the exception of the haptic feedback provided by the simulator, all the other phases (baseline, transfer and retention) were performed under no feedback condition.

2.5 Data collection and statistical analysis

CKAT performance was analysed using *R* (R Development Core Team, 2015); see (49) for a detailed description of the methodology of analysis . Dental task performance was captured using the following metrics provided automatically by the simulator: Task completion (%), Drill Time (seconds), Leeway Errors scores % (separately for sides and bottom) and Container Errors scores % (separately for sides and bottom). A composite error score was calculated by combining the z-scored means of both Leeway and both Container error scores.

A one-way analysis of variance (ANOVA) with group as a factor was conducted on the baseline (pre-test) scores for each performance measure to identify the initial differences amongst the three groups. Operational definitions of the performance measures are shown in **Table 2.** In order to examine the performance at experimental stages, the following repeated measures ANOVAs were conducted. At Training, we conducted a 3 (Group; DFB vs. IFB vs. IDFB) x 4 (Time [Exercise Session 1 vs. 2 vs. 3 vs. 4) ANOVA; for Transfer a 3 (Group) x 2 (Transfer Test 1 vs. 2) ANOVA; and for Retention, a 3 (Group) x 3 (Time; Immediate vs. Week vs. Month) ANOVA.

All data were tested for departures from normality by boxplot, Q-Q plots, histograms and Shapiro-Wilk test ($p < .05$) with transformations performed where necessary. Where transformations did not yield normally distributed data (i.e. container error scores), non-parametric tests (Kruskal-Wallis) were performed. Where assumption of sphericity was violated (as indicated by Mauchly's test), Greenhouse Geisser corrected *p* values are reported. The statistical significance threshold was set to $p < .05$. Bonferroni-corrected post hoc comparisons were performed where significant main effects were found. Partial eta squared values (η_p^2) are reported to indicate effect size. One-way ANOVAs were applied to estimate between-group differences on each training exercise separately whenever significant interactions where encountered. All statistical analyses were performed using IBM SPSS® Statistics for Windows (Version 22, Armonk, NY: IBM Corp., 2013).

Table 2 Operational definitions of performance measures

Performance measures	Operational definition
Task completion (%) TC	The amount of the target removed by the participant. For the tasks conducted here, 70% reflected a reasonable performance level.
Drill Time (preparation time) in seconds DT	The total time taken by the participant to drill the shape
Error scores (%)	Error scores were defined as those when drill movement extended beyond the safe/designated margins of a given shape (see Figure 1B) and were computed as a percentage of the total region (leeway/bottom)

3 Results

3.1 Overall composite error scores

The overall Composite error scores were significantly different among the Groups, [*F* (2,60) = 5.63, *p* = .006, η_p^2 = .158] with the IDFB having significantly lower error scores (*M* = 13.68, *SD* = 5.6) than DFB (*M* = 21.4, *SD* = 9.6; see **Figure 2**.

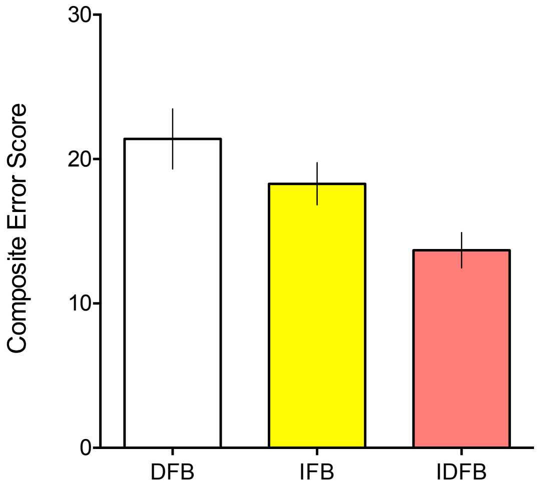

Figure 2. The overall composite error scores among the 3 feedback groups: [DFB] Device Feedback group, [IFB] Instructor Feedback group, [IDFB] Instructor Device Feedback group. Error bars represent ±1 SEM.

3.2 Performance at baseline test

At baseline (BL), there were no significant differences (F's < 2.86, *p*'s > .065) among the groups in any of the performance measures (DT, TC, Leeway errors A scores, Container errors B scores), indicating a relatively similar basic skill level.

3.3 Performance at training phase

There were no significant differences among groups in the total time taken to perform the task (drill time) during all training exercises, [F (2.52,151) = 1.078, *p* = .4, η_p^2 = .018]. However, significant main differences among the groups in the task completion percentage (i.e. how much of the target zone was removed) were found, [*F* (3.6, 109) = 7.06, *p* = .001, η_p^2 = 0.19]. Post hoc analysis revealed that DFB group had significantly higher TC scores than other groups in the first (*p* = .001) and the fourth (*p* = .004) training exercises.

For the Leeway errors (A)**,** the leeway sides' error scores (LS) were significantly different among the groups during training, [*F* (2.7, 162.35) = 18.5, *p* < .001, η_p^2 = 0.24]. Post hoc analysis revealed that IDFB group had significantly lower error scores than the other groups during first (*p* = .007), second (*p* = .045), and fourth (*p* = .039) training exercises. Similarly, the leeway bottom error scores (LB) were significantly different among the groups during training, [*F* (2, 121.7) = 542.5, *p* < .001, η_p^2 = 0.9]. Post hoc analysis revealed that the IDFB group had significantly lower error scores than the other groups during first (*p* = .002), and second (*p* = .024) training exercises. The Container error (B) scores **(**bottom and sides) were not significantly different among the groups during training phase ($\chi^2{}_{(2)}$< 4.2, *p* > .120).

3.4 Performance at transfer (generalisation) tests

Drill time was significantly different among groups during transfer tests, [*F* (2,60) = 5.75, *p* = .02, η_p^2 = .87]. Post hoc analysis revealed that during the second transfer test, the IFB group took a significantly longer time to perform the 2nd transfer test (M = 99.95 s, SD = 57.2) than the DFB group (M = 64.67 s, SD = 36.4). The other performance parameters were not statistically significant; TC [*F* (2,60) = 0.337, *p* = .56], and error scores [*F* (2,60) = 2.17, *p* = .12] among the groups during the transfer tests (see Figure 3B).

3.5 Performance at retention tests

During the three retention post-tests (Figure 3), drill times were not significantly different between groups [F (2,60) = 0.83, *p* = .44, η_p^2 = 0.027]. Additionally, no significant differences were found when the BL test compared to retention tests' drill times [*F* (2.3,139.15) = 0.757, *p* = .48, η_p^2 = .012].

Task completion percentages were significantly different among groups during the retention tests, [*F* (1.8,108.5) = 614.2, *p* <. 001, η_p^2 = 0.91] with the 2nd retention test (one-week post-test), IFB group showing a significantly higher percentage of TC than IDFB (*p* = .017).

The Leeway sides' (LS) error scores were significantly different among the groups during the 2nd retention test (one-week post-test), [*F* (2,60) = 4.027, *p* = .023], as well as during the one-month retention test, [*F* (2,60) = 6.5, *p* = .003]. IDFB had significantly lower LS scores than IFB (*p* = .019) and DFB (*p* = .004) groups. The Leeway bottom scores (LB), the container bottom (CB) and container sides' scores (CS) were not significantly different among groups during retention tests, *p* > .05.

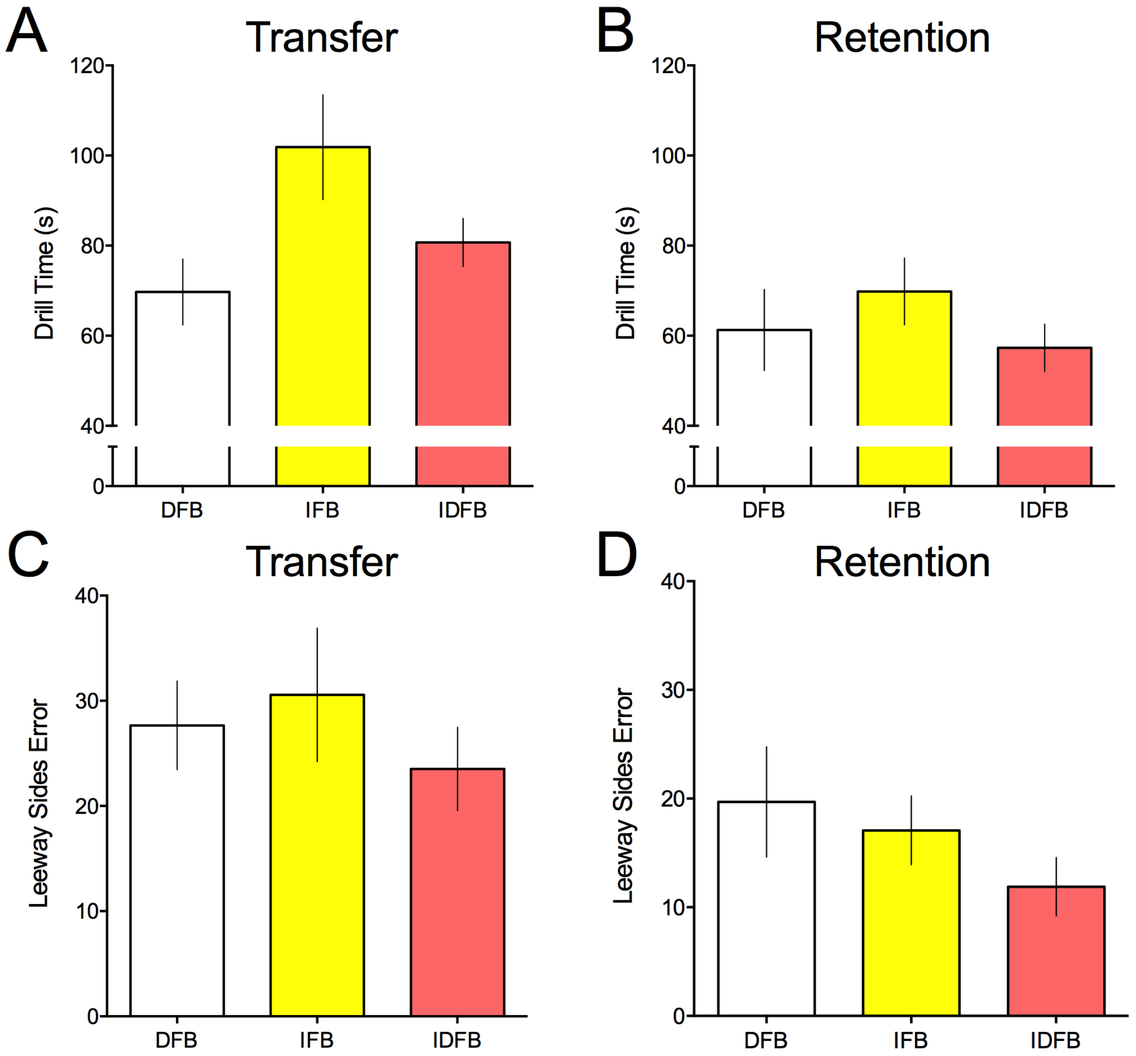

Figure 3 Transfer and Retention. Mean Drill time for the three groups at transfer (A) and retention tests (B); (Mean Leeway side error scores at transfer (C) and retention (D) tests. Error bars represent ±1 SEM.

3.6 Performance and fine motor control abilities:

The CKAT scores did not significantly differ between groups, [F (2,60) = 1.365, p = .263, η_p^2 = .044]. A Spearman's rank-order correlation was performed to assess the relationship between the overall performance scores and CKAT battery scores. There was no correlation between CKAT and performance, [r_s (61) = 0.04, p = .758] or errors [r_s (61) = 0.128, p = .319].

4 Discussion

Novice participants were taught a basic manual dexterity task within a VR haptic simulator using qualitatively different types of feedback during training. The data indicate that the participants who received a combination of instructor-led and VR haptic simulator feedback adopted a more cautious strategy than those who were exposed to one type of feedback alone. Specifically, these participants produced fewer errors and also removed less of the target than the other groups. We suggest that such behaviour is potentially advantageous for novice trainees - producing safer practice relative to an over ambitious student sacrificing accuracy for greater target removal.

Importantly, we also demonstrated that the presence of VR devices alone is not sufficient for optimal training of motor skills and must be coupled with expert guidance- at least at the early stages of training. Our findings are consistent with the motor learning and medical literature indicating that multimodal feedback is more effective than unimodal feedback- particularly during the early acquisition of complex skills (21,51). Whilst others have previously shown the value of providing augmented visual feedback with additional tuition sessions prior to training (39), our work presents the first set of data demonstrating the value of haptic simulator feedback combined with continuous instructor feedback in motor skill acquisition and retention.

The finding that the group who received feedback from the device alone was the lowest performing throughout the experiment is instructive for the teaching of motor control skills in dentistry. Research on motor skill acquisition indicates the existence of two broad mechanisms that interact and contribute to learning any given motor task (52). The most rapid method of improving task performance is known as “model-based” (MB) learning and depends upon previously developed ‘forward models’ that allow the actor to make predictions about the consequences of their actions. This is the type of mechanism that most likely underlies the process of learning to use loupes (i.e. where an experienced dentist will use existing knowledge about task-related perceptual information to calibrate to a new visual environment in order to perform a task). Although MB learning is initially a cognitively expensive activity, the speed of skilled acquisition can lead to relative automaticity of performance in a short period of time. The second form of learning is known as “model-free” (MF). This learning involves the development of ‘inverse models’ or ‘controllers’ via trial and error learning and is a slower process. MF learning is an essential component of skill acquisition and would underpin the learning process within all three of our experimental groups. But the provision of additional information allows individuals to exploit MB learning processes and generalise their skills to situations that have not been previously encountered. In line with this framework for understanding motor learning, the present data suggest that excessive error can be reduced through guidance from an external source such as an experienced instructor (i.e. the DFB group). This guidance provides information that can be used rapidly to develop forward models specifying appropriate task-related actions. Evidence that participants in the IDFB group were able to achieve such a feat is demonstrated by the finding that their skill levels were consolidated over time and that information learnt in one task could be generalised to another, thus demonstrating rapid near transfer (53) - a hallmark of MB processes.

It is worth noting that whilst reducing error through instructor feedback was useful for our sample of novice trainees, error augmentation could provide a more effective means of accelerating learning in a group with a higher level of skill (54). In other words, the amount of assistance and pedagogical feedback provided to final year undergraduates to achieve mastery of a task is likely to be qualitatively different to the optimal strategy for trainees earlier in their training. Task difficulty is also likely to modulate the relationship between optimal feedback and motor learning. For example, the optimal feedback for a basic manual dexterity exercise might be different to that required for a Class II cavity preparation or during the application of restorative materials. It follows that the type of feedback provided during preclinical and clinical dental training needs to be carefully considered and investigated in order to ensure optimal learning.

Taken together, these results raise an important question about how to integrate VR into dental education in a cost-effective manner. A proposed strength of haptic VR simulators is that they allow students to increase the number of hours they put into practice without increasing staff demands- but these data show that learning with and without instructor feedback is not equivalent. Future work should examine how many hours of independent practice is comparable to one hour of tutor driven feedback.

Finally, exploring the full potential of these systems in accelerating motor skill acquisition independent of tutor supervision is desperately needed. Work is currently underway to examine whether the haptic technology present in these systems can be used to manipulate movement- for example through the provision of assistive and/or disruptive forces to accelerate skill motor skill learning.

4.1 Conclusions

The learning of basic manual dexterity skills was accelerated when participants were provided with haptic device feedback in conjunction with an experienced dental instructor, relative to groups with access to the device only or instructor only feedback. This was particularly beneficial for the retention of learned skills. There was an overall performance improvement for all groups at the end of the experiment (retention phase), which was evidenced by lower error scores as well as comparable time for task performance (DT).

These data indicate that integration of VR into a dental curriculum needs consideration in order to maximise VR's potential utility in motor skill learning and to complement existing simulation techniques. Future research should address the feasibility of integrating multi-modal simulation and examine whether combining the best features of virtual reality-based and traditional non-computerized simulation approaches can enhance motor skill acquisition. Furthermore, the long-term effects of VR delivered training are relatively unknown, as are individual differences (e.g., the influence of different levels of stereoacuity (55)) and these issues require further exploration.

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