Haptic-Enhanced Learning in Preclinical Operative Dentistry

By

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The candidate confirms that the work submitted is her own, except where work which has formed part of jointly-authored publications has been included. The contribution of the candidate and the other authors to this work has been explicitly indicated below. The candidate confirms that appropriate credit has been given within the thesis where reference has been made to the work of others.

1. The paper listed below forms the basis of Chapter 6 in this thesis. The candidate is the primary author and she completed all experimental studies, evaluation of data and preparation of publication. The named co-authors provided support through review and proofreading prior to publication.

   Al-Saud LM, Mushtaq F, Allsop MJ, Culmer PC, Mirghani I, Yates E, Keeling A, Mon-Williams MA, Manogue M. **Feedback and motor skill acquisition using a haptic dental simulator.** *European Journal of Dental Education. 2016 Jun 21. doi:10.1111/eje.12214. PubMed PMID: 27324833.*

2. The paper listed below has been accepted for publication (January 6, 2017). It forms the basis for section 1 of Chapter 5 of this thesis. The candidate is the primary author and the named co-authors provided support through review and proofreading prior to publication.

   Al-Saud LM, Mushtaq F, Mirghani I, Keeling A, Manogue M., Mon-Williams MA. **Drilling into the functional significance of stereopsis: The impact of stereoscopic information on surgical performance.** *Journal of Ophthalmic and Physiological Optics*.

3. The work was also disseminated through a conference presentation (oral) by the candidate. The following presentation contributed to Chapter 5 of this thesis:

   Al-Saud LM, Mushtaq F, Mon-Williams MA, Manogue M. **Investigating the role of Stereopsis in Dental Performance using Virtual Reality Haptic Simulator.** In Association for Medical Education in Europe (AMEE) Conference, 2016, Barcelona, Spain.

Disclaimer:

The candidate confirms that she has no financial or non-financial interests in the Dental Simulator (Simodont®) or any other device described in this PhD thesis. Further, she confirms that she has no affiliations with Moog Inc. or ACTA.

Dedication

I dedicate this thesis to my precious mother (Sarah).. the light of my soul.. for her unconditional love, friendship, wise advice, patience and generous support every step of the way. May Allah grant her good health and happiness always and forever.

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Loulwa

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Abstract

Background: Virtual reality haptic simulators represent a new paradigm in dental education that may potentially impact the rate and efficiency of basic skill acquisition, as well as pedagogically influence the various aspects of students' preclinical experience. However, the evidence to support their efficiency and inform their implementation is still limited.

Objectives: This thesis set out to empirically examine how haptic VR simulator (Simodont®) can enhance the preclinical dental education experience particularly in the context of operative dentistry. We specify 4 distinct research themes to explore, namely: simulator validity (face, content and predictive), human factors in 3D stereoscopic display, motor skill acquisition, and curriculum integration.

Methods: Chapter 3 explores the face and content validity of Simodont® haptic dental simulator among a group of postgraduate dental students. Chapter 4 examines the predictive utility of Simodont® in predicting subsequent preclinical and clinical performance. The results indicate the potential utility of the simulator in predicting future clinical dental performance among undergraduate students. Chapter 5 investigates the role of stereopsis in dentistry from two different perspectives via two studies. Chapter 6 explores the effect of qualitatively different types of pedagogical feedback on the training, transfer and retention of basic manual dexterity dental skills. The results indicate that the acquisition and retention of basic dental motor skills in novice trainees is best optimised through a combination of instructor and visual display VR-driven feedback. A pedagogical model for integration of haptic dental simulator into the dental curriculum has been proposed in Chapter 7.

Conclusion: The findings from this thesis provide new insights into the utility of the haptic virtual reality simulator in undergraduate preclinical dental education. Haptic simulators have promising potential as a pedagogical tool in undergraduate dentistry that complements the existing simulation methods. Integration of haptic VR simulators into the dental curriculum has to be informed by sound pedagogical principles and mapped into specific learning objectives.

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List of Abberevations

2D	Two Dimensional
3D	Three Dimensional
AR	Augmented Reality
AV	Augmented Virtuality
CA	Continuous Assessment
CKAT	Clinical Kinematic Assessment Tool
CT	Computed Tomography
DAT	Dental Aptitude Test
FOV	Field of View
GPA	Grade Point Average
HEFCE	Higher Education Funding Council for England
HF	Human Factors
KP	Knowledge of Performance
KR	Knowledge of Result
MIS	Minmally Invasive Surgery
MMI	Multiple Mini Interviews
MRI	Magantic Resonance Imaging
NPV	Negative Predictive Value
PFM	Porcelain Fused to Metal
PPV	Positive Predictive Value
RDSs	Random Dot Stereograms
UKCAT	United Kingdom Clinical Aptitude test
VE	Virtual Environment
VR	Virtual Reality
WHO	World Health Organization

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Chapter 1 : Introduction

1.1 Introduction

In dentistry, intensive theoretical and practical preclinical training is fundamental to undergraduate dental education experience. Fine motor skills are honed through simulation-based training using the renowned phantom head simulator with plastic teeth.

Recently, the vast advancement in virtual reality (VR) technology has unlocked exciting new avenues for simulation-based education via advanced interfaces and safe virtual environments with powerful and flexible features. Therefore, virtual reality simulators (with and without haptic technology) have been increasingly adopted across many dental schools around the world. Concomitantly, a growing body of literature has emerged that recognize the importance of these simulators in dentistry and advocate their use in various dental training contexts such as manual dexterity and basic skills training, implant dentistry, oral and maxillofacial surgery.

Despite the increased adoption of such simulators into dental education, they are still considered in their early stages in terms of development, design features, applications and utility. Furthermore, many aspects of virtual reality simulation training particularly with haptics remain under-examined and lack empirical evidence that support their use based on pedagogical principles. The implementation of any technology in pedagogical contexts is professionally, logistically and financially demanding, and virtual reality simulators are no exception. Therefore, it is crucial to critically evaluate many factors before their full adoption into the curriculum.

There is a need to empirically scrutinize the existing simulators in the context of dental training and education to identify their potential utility as pedagogical tools and to inform their future design improvement.

The achievement of such a goal is not an easy research mission, due to the inherently broad and multifaceted nature of the topic, that demands collaborative research efforts from various disciplines including dentistry, education, engineering, cognitive psychology, and computer sciences.

1.2 Aim

The general aim of this research project is to evaluate the effects of a haptic dental simulator (Simodont®) on the learning of basic dental fine motor skills in the context of preclinical operative dentistry.

1.3 Research motivation

The current thesis is motivated by the following research questions:

1. How virtual reality dental simulators with haptic technology would enhance the preclinical experience of undergraduate dental students?
2. Can haptic dental simulator predict future preclinical and clinical performance?
3. What factors would affect the utility of such simulator?
4. How they can be effectively integrated into the dental curriculum?

1.4 Objectives

For a focused approach to this research investigation, we specify 4 research themes to explore through cross-sectional studies: fine motor skill acquisition, human factors (HF) in 3D stereoscopic display, prediction of future dental performance, and curriculum integration.

The objectives of the current research project are:

1- To explore the validity of Simodont® early training in predicting subsequent preclinical and clinical performance.
2- To investigate the role of stereopsis (depth perception resulting from binocular retinal disparities), in dentistry and its influence on preclinical and clinical dental performance using VR simulator.
3- To investigate the role of pedagogical feedback, as a critical factor in simulation-based education, on the training, transfer and retention of basic manual dexterity dental skills using Simodont®.
4- To design a pedagogical model for integration of virtual reality haptic dental simulator into undergraduate dental curriculum.

1.5 Thesis outline

The manuscript of this thesis is structured into 8 chapters.

Chapter 1 introduces the thesis background and defines its aim, motivation and objectives, with outline of the thesis structure. The relevant literature is reviewed in **Chapter 2**, focusing on the principles of motor skill learning, medical and dental simulation, virtual reality and haptic technologies. Further focused review of literature is presented at the beginning of each of the following four chapters.

The scope of the next two chapters is the simulator validity. In **Chapter 3**, the face and content validity of the Simodont® is explored, while the predictive validity of the Simodont® is investigated in **Chapter 4**.

Chapter 5 focuses on stereopsis, as an important human factor issue that potentially influences the utility of virtual reality simulators. This chapter is organised into two sections, reporting two studies about stereopsis in dentistry from different perspectives, each with distinct experimental approach and participants. The first study investigates the impact of removing stereopsis within the stereoscopic display in Simodont® VR simulator (whilst leaving other information unaffected) on the performance of postgraduate dentists in standard dental tasks. The second study explores the association between undergraduate students' stereoscopic acuity levels and their practical dental performance in preclinical operative dentistry course.

Chapter 6 is an investigation into the role of pedagogical feedback on motor skill acquisition among novice participants with no previous dental training. The chapter provides an in depth discussion of the role of feedback from its various sources (educator, simulator) and how it influences the acquisition of fine motor skills in VR simulated setting.

Chapter 7 focuses on how the haptic dental simulator can be integrated effectively into the undergraduate dental curriculum by proposing a pedagogical integration model with a theoretical foundation. The proposed model aims to not only integrate the haptic simulator, but also to provide a recommendation to restructure the undergraduate dental experience to incorporate wider pedagogical concepts that have been underutilised, but have the potential to better prepare dental students for clinical practice.

Finally, **Chapter 8** provides a general discussion of the findings and the overall conclusions. Additionally, thesis limitations and suggestions for future work are presented.

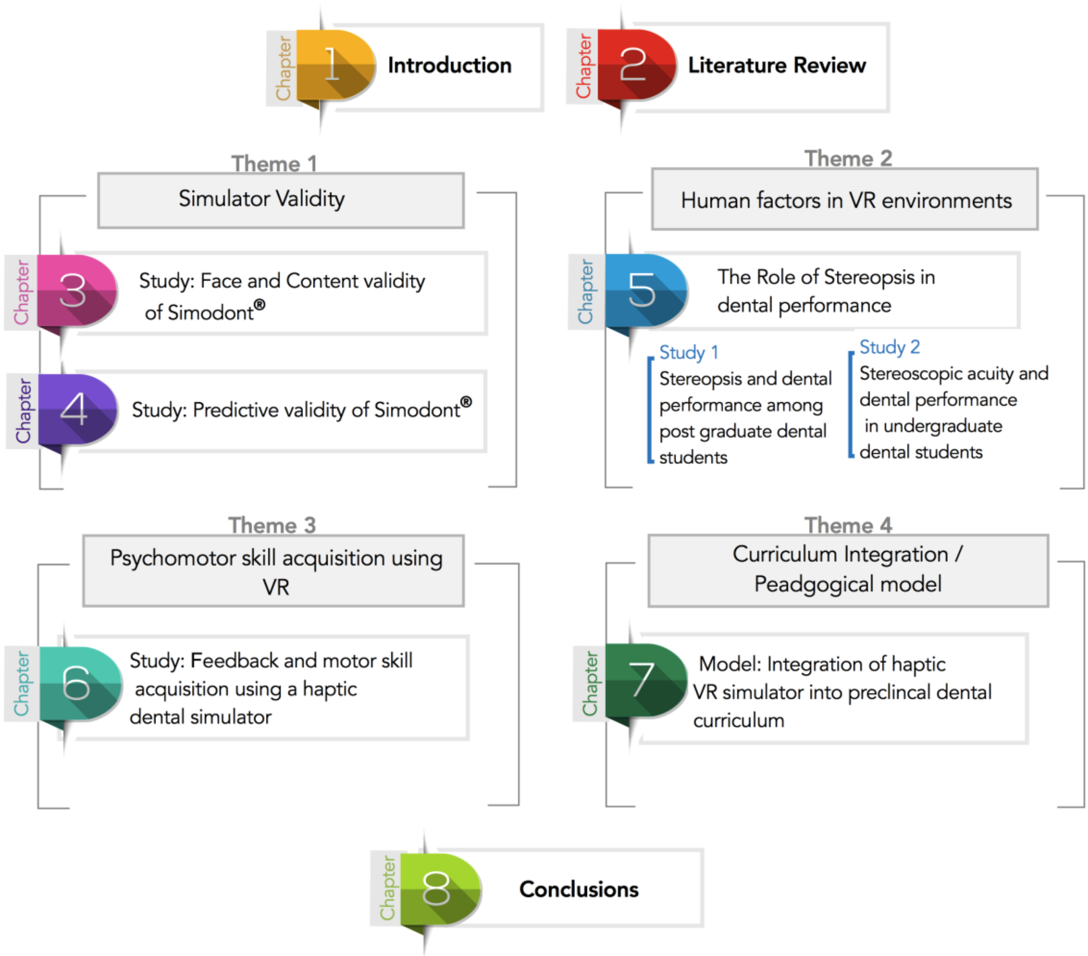

Figure 1-1 Thesis schematic outline.

Chapter 2 : Literature Review

The goal of undergraduate dental education is to provide an effective learning environment that fosters the development of dental students into competent dentists. Competency comprises academic knowledge, clinical skills and professional attitudes, which defines the minimum acceptable performance level for a dentist at the time of graduation capable of safe, effective and independent dental practice (Plasschaert et al. 2007; Cowpe et al. 2010).

One of the most important objectives in undergraduate dental education is the learning of fine sensorimotor skills (Evans & Dirks 2001). Although learned early in dental school, these skills continue to evolve over the years of dental practice. This learning must be achieved in concert with broad foundation knowledge of basic health and dental sciences, as well as other important skills such as teamwork, effective communication, problem solving, treatment planning, and decision-making.

Dental students start providing supervised treatment to real patients relatively early in their career (3rd or 4th year in most dental schools) compared to other healthcare professionals. This demands a clinically acceptable level of highly specific sensorimotor skills, such as hand-eye-finger coordination, spatial perception (Evans & Dirks, 2001) mirror (indirect) vision, use of finger support, precise instrument handling and other skills to perform dental procedures safely and effectively in the unique oral environment, which is challenging in many ways:

- Working with delicate oral tissues (e.g. lips, cheeks, teeth, tongue, and gingival tissues) in the presence of saliva, blood and other oral fluids.
- Restricted access environment, with limited range of movements.

- The manipulation of specialised, relatively small, dental instruments with precise movement and coordination, which require a high level of manual and finger dexterity.
- Performance of specific dental procedures, the majority of which are invasive and irreversible (e.g. tooth cutting and preparation)

Therefore, due to the nature of the profession, dental education has been always reliant on simulators for teaching sensorimotor skills more than any other health specialty (Levine et al. 2013). This learning takes place primarily in the simulation laboratories and within the context of operative dentistry. Operative/restorative dental sciences are the foundation of almost all other dental specialties and the area to which most of the preclinical teaching time is dedicated (Ferguson et al. 2002) . It is a constantly evolving speciality that is continuously updated with more understanding of the carious process, its risk assessment and management approaches with a variety of new restorative materials and treatment techniques, that demand highly specific skills and an on-going practice using simulation, even at the postgraduate level. This is particularly true as minimally invasive dental (MID) procedures are being progressively employed for maximum conservation of tooth structure (Walsh & Brostek 2013; Frencken et al. 2012).

Beyond sensorimotor skill learning, simulation is needed to facilitate the transition into the dental clinic, to augment ergonomics and to enhance the students' preclinical experience through inclusion of a wide range of simulated patient scenarios (Hollis et al. 2011) emphasising a holistic approach to patient management.

From G.V. Black's giant tooth models and Fergus's phantom head (Mason

2005) to high fidelity virtual reality simulators and robotics, dental education has come a long way in the realism of the preclinical simulation experience, which continue to be an integral part of undergraduate dental education.

Effective instruction in preclinical dentistry is multidimensional and requires broad knowledge not only of dental sciences but also educational methodologies, assessment best practices, and thorough an understanding of basic principles of motor skill acquisition.

The first section of this chapter is an overview of the concept of simulation and simulation-based education in medicine and dentistry.

2.1 Simulation

Simulation is a methodology that replicates or amplifies real experiences with directed experiences using analogous tools or settings that imitate real world conditions, with the goal of learning and training, in an immersive and interactive mode (Gaba 2004; Littlewood 2011). For many years, simulation has been effectively utilized for education, assessment, and maintenance of various skills across diverse domains especially in complex professions which demand a high degree of precision and safety such as aviation (for pilot and crew training), and for the military (Issenberg et al., 2005). The earliest evidence of simulation efficacy in training came from the performance improvement of pilots in aviation training, which made flight simulation an integral part of the aviation industry to maintain the high safety standards (Levine et al. 2013; Littlewood 2011; Allerton 2010).

Simulation in healthcare education is not new, and has been utilised as a learning tool as early as the 19th century (e.g. anatomy models), however, it has evolved now into a distinct pedagogical modality (Bradley 2006). It is an educational methodology to replicate real patient care scenarios in a controlled environment, to achieve pre-defined learning objectives, using artificial models, standardized patients or virtual reality devices for the purpose of improvement of individual and team performance in a health care system. It is a standardized educational medium for training, rehearsal, assessment and maintenance of a wide range of skills across multiple healthcare disciplines, in a safe and ethical environment that enhances the learning tasks' predictability, consistency, and reproducibility without jeopardizing patient safety (Okuda et al. 2009; Sevdalis et al. 2016; Gaba 2004; Cheng et al. 2016). Simulation is particularly suited for formative assessments, where the learners are provided with immediate constructive feedback on their task performance in a simulated environment (Damassa & Sitko 2010).

Simulation methodology include special devices, partial or full patient simulators, that provide appropriate interaction media in response to the participant's actions and manipulation (Gaba 2004). They span a wide range of fidelity (the level of realism of a simulated condition or setting) and can be simply categorised into part task trainers, full body computer-enhanced mannequins, and virtual reality simulators (Scalese et al. 2008). Although the majority of simulators in health care education are designed for learning of procedural skills (e.g. MIS-minimally invasive surgery, obstetrics, dentistry), soft skills (or non-technical skills) such as communication skills, team work, and decision making can also be learned effectively using structured simulation settings (Gaba 2004).

The availability of simulators and advancement in their fidelity does not preclude the need for faculty well trained in pedagogical principles (Okuda et al. 2009), it actually emphasise their central role in various simulation-based educational settings. Although simulation is an adjunctive methodology and not a substitute for real clinical practice, if well planned and effectively utilised it improves the trainee competence and confidence in real world settings (Levine et al. 2013).

The simple distinction between simulation as an event and simulator as a tool, is advocated to emphasise that both should synergistically compliment the educational experience of a health care professional, and underpin any scientific investigation into the simulation-based education. In other words, simulation is a unique learning opportunity that must be well planned and implemented in a controlled environment as part of a wider structured curriculum, whereas simulators are tools that form a valuable part of the simulation experience (Dutta et al. 2006).

Simulation has become fully integrated into the clinical training of undergraduate medical students, postgraduate surgical residents as well as for continuing professional development (Issenberg & Scalese, 2007).

In the recent guidelines for Transforming and Scaling up Health Professionals' Education and Training, the World Health Organization (WHO) strongly recommend the use of simulation methods with fidelity levels appropriate for various training/education contexts in health profession education. Additionally, it recommends several research activities to bridge the knowledge gaps in the use of simulation methods such as the long-term impact on learner's performance, and the effect on patient outcomes (WHO 2014).

These recommendations highlight the fact that simulation is unique and versatile not only as an education and training methodology but also as investigational research tool (Littlewood 2011), therefore, simulation based research has grown exponentially in recent years (Sevdalis et al. 2016), albeit with great inconsistency among studies, which highlight the need for improvement and standardization of the quality of the reported research in the field. Recently, Cheng and colleagues published the first reporting of guidelines for the use of simulation in health care research by creating extensions to the CONSORT (Consolidated Standards of Reporting Trials statement for randomised trials) and STROBE (Strengthening The Reporting of OBservational studies in Epidemiology) statements (Cheng et al. 2016). The guidelines are necessary to guide the research efforts into systematic, unbiased, scientifically sound approach for health care simulation research which should provide common language that recognize the value of research findings beyond any contextual differences.

2.1.1 Simulation-based medical education

The classical approach to surgical training is the apprenticeship model "see one, do one", where the novice trainee is learning from the expert while treating patients in the clinical environment. This long-standing, teacher-centred approach served well as the gold standard for many years since the early days of surgical training (Levine et al. 2013). However, this apprenticeship model has been challenged in recent years (Brydges et al. 2007; Grantcharov & Reznick 2008), and a paradigm shift in the field of surgical education has been witnessed (Sachdeva et al. 2011; Alaker et al. 2016). This has been driven by several factors, including the increased emphasis on patient safety; the need to expand the educational experience of the trainee to include a wide range of new skills imposed by advances in knowledge base, surgical tools and technology (e.g. MIS), despite the reduction in annual training hours of residents that translate into less likelihood of case-specific clinical training opportunities. Additionally, the need to give the trainee a standardized educational experience that is structured, well planned and caters for individual learning differences; and the need to provide a safe, controlled learning environment that promotes learning, and facilitates training for all skill levels with opportunity for deliberate practice (McCaskie et al. 2011; Cosman et al. 2002; Motola et al. 2013; Bradley 2006; Grantcharov & Reznick 2008; Konia & Yao 2013).

Therefore, simulation-based education has emerged as a distinct field to bridge the educational gap between theory and practice on real patients, and as an essential intermediate stage between “see one, and do one” (Akaike et al. 2012).

From a motor skill perspective, the technological advances in the surgical armamentarium have led to more utilization of minimally invasive surgical modalities and shifting away from traditional open surgery. This approach has modernised surgical care and profoundly impacted surgical outcomes (i.e. minimal incisions, less trauma to the patient, reduced hospital stay and recovery time, etc.). However, these technology-enhanced surgical techniques introduce a new interface (e.g. 2D screen in laparoscopic surgery) between the surgeon and the tissues, which potentially affects the interaction modes and subsequently the performance (Tanagho et al. 2012).Therefore, surgeons need to learn and be competent at a new set of cognitive and sensorimotor skills before performing any surgical procedure in the operating theatre, which demands intensive training. This shift has led to increased adoption of VR simulators, along with other simulation modalities, in many surgical training programs for skill training, maintenance and for assessment and objective evaluation of surgical competency. VR simulation training becomes an essential step in the early stages of sensorimotor skill acquisition particularly in laparoscopic surgery, where the research findings showed its impact on improved operative performance with reduction of the operative time (Cosman et al. 2002; McCaskie et al. 2011; Alaker et al. 2016; Scalese et al. 2008; Okuda et al. 2009). The technological advances in image processing, and computer software and hardware paved the way for progressively sophisticated, highly realistic VR simulators in terms of their design features, fidelity and expanded utility. For example, Patient- specific virtual reality simulation (PSVR), is a technique in which a VR simulator is used to perform patient specific surgical rehearsal (or warm-up) based on real patient imaging data (e.g. from Computed Tomography-CT- or MRI). This technique aids in intervention planning and potentially impacts the operator preparation level not only technically but also in non-technical aspects such as decision-making, and teamwork training (Willaert et al. 2012).

2.1.2 Simulation-based dental education

2.1.2.1 Phantom head simulators:

More than 100 years ago, the concept of the phantom head simulator was introduced by Oswald Fergus to improve ‘the preliminary instruction’ (Mason 2005) and the realism of the dental training. Fergus’s phantom head was designed to be used in the laboratory and be attached to the dental chair (Perry et al. 2015). Since then it has undergone many design refinements and modifications to improve and expand its utility. The simulated maxillary and mandibular jaws (Typodont/ Dentoform) are becoming increasingly realistic, simulating various dental diseases (e.g. periodontitis, caries) and include the full set of individual anterior and posterior plastic teeth (permanent and primary) that can be removed, replaced and adjusted as required.

Today, phantom head simulators with typodont are considered the gold standard for undergraduate preclinical teaching as well as for postgraduate skill training in most dental schools around the world (Gottlieb et al., 2013). The phantom head simulator is a partial task trainer, with simulated torso, that facilitates the learning of fine sensorimotor skills and tooth preparation and restoration procedures in a safe environment (Fugill 2013). They are versatile and reliable educational tools of relatively low initial cost that have been in use for a long time (Ben Gal et al., 2011). However, the plastic teeth used in these mannequins lack the real tactile sensation of natural layers of tooth structure (i.e. enamel and dentine) and there is a constant need for unit and handpiece technical maintenance as well as constant availability of disposable training resources (plastic teeth, burs, etc.).

2.1.2.2 Virtual Reality-based simulation

With the continuous technological advances, computer assisted dental simulators have been developed based on virtual and augmented reality technology. Computer software is used to create a virtual reality environment based on mathematical models that allow users to interact and navigate through the virtual world similar to real life. The unique feature of VR simulators is the availability of objective real-time feedback on student performance, in addition to the feasibility of iterative practice without the need for additional resources (plastic teeth, burs, etc.). Therefore, VR simulators were reported to be particularly effective for formative assessment and evaluation that is facilitated by immediate and post practice feedback (e.g. video recordings), as well as in enhancing fine motor skill acquisition rate (Buchanan 2001; Shahriari-Rad 2013; Vervoorn et al. 2015).

Compared to traditional simulators, haptic VR simulators were also reported to enhance the student learning via improved hand-eye coordination and self-reflection (Cox et al. 2015) . Additionally, learners with low visual-spatial ability seem to benefit more from VR simulation training than conventional training (Nilsson et al. 2007).

A. <u>Augmented Reality dental simulators:</u>

The first VR simulator for dental education, the DentSim (Image Navigation Ltd., New York), was developed in the late 1990's (Rose et al. 1999; Dutã et al. 2011) and it is the most widely investigated in the literature.

The DentSim system is based on augmented reality technology, in the sense that a phantom head with plastic teeth and handpiece is still used (real tools) augmented with special computerised 3D graphics and optical sensors that provide auditory and visual feedback. It is based on GPS (global positioning system) technology, and it tracks the position of the manikin jaws and handpiece via LED sensors. The computer screen is attached to the unit and it shows 3D representation of the preparation with real-time quantitative feedback and detailed evaluation of performance (compared to an ideal preparation in the database)(LeBlanc et al. 2004; Levine et al. 2013).

In a comparative study Jasinevicius et al. (2004)compared the DentSim virtual reality simulator to the non-computerised phantom head simulator in terms of student-faculty interaction (time, and type of feedback requested) and preparation related factors (number of preparations, time spent and the quality of the preparations). Although the quality of the preparations done by both groups were comparable, the students trained with virtual reality simulators needed significantly less instructional time from the faculty than the other group. Therefore, it has been suggested that virtual reality simulators may provide a self-directed learning approach of sensorimotor skills (Jasinevicius et al. 2004). Similarly, Buchanan (2004) reported that students who were trained with (DentSim) learned faster, performed equally well, and carried out more procedures than students who were trained in traditional laboratories (Buchanan 2004). Therefore, virtual reality simulation using (DentSim) is considered an effective approach for skill development especially in operative dentistry compared to traditional simulation (LeBlanc et al. 2004); and training sessions in both laboratories can be effectively alternated for manual dexterity training, with the provision of appropriate feedback (Wierinck et al. 2006). Urbankova (2010) highlighted the importance of immediate feedback gained from the DentSim simulator especially at the early stages of dental skill acquisition; and advocated the integration of simulation technology at the beginning of the preclinical experience (Urbankova 2010).

Collectively, the evidence from studies on DentSim suggests its effectiveness as a training tool as it shortens the learning curve of operative procedural skills, minimises faculty instruction time and provides objective immediate feedback.

Another augmented reality based simulator is CDS-100 (EPED INC., Taiwan) that is similar in concept to the capabilities of DentSim, albeit not as thoroughly researched (Gottlieb et al. 2013).

B. Haptic Simulators:

The advancement of haptic technology has produced a step-change in the virtual reality world and specifically on dental simulator development. Dental simulators that include haptic technology fundamentally change the way one interacts with virtual objects by providing realistic feel and touch sensation (Gottlieb et al. 2013). Haptic VR simulators transfer the simulation experience, almost entirely, to the virtual world (i.e. no phantom head, plastic teeth, real typodonts, or real handpiece).

The speed of development in the design and features of various haptic dental simulators was not always matched by empirical research into their pedagogical effectiveness, especially large-scale longitudinal investigations. However, cumulative evidence of their utility in dental education is currently emerging in the literature, and VR simulators are gaining momentum in the dental community and increasingly being implemented by dental schools around the world that support this type of pedagogical innovation (Eaton et al. 2008; Vervoorn et al. 2015). Currently, there are a number of commercially available haptic dental simulators that has been utilised and investigated in the literature, such as Simodont® (Moog Inc., The Netherlands), VOXEL-MAN Dental (VOXEL-MAN, Germany) and VirTeaSy® Dental (HRV-simulation, France).

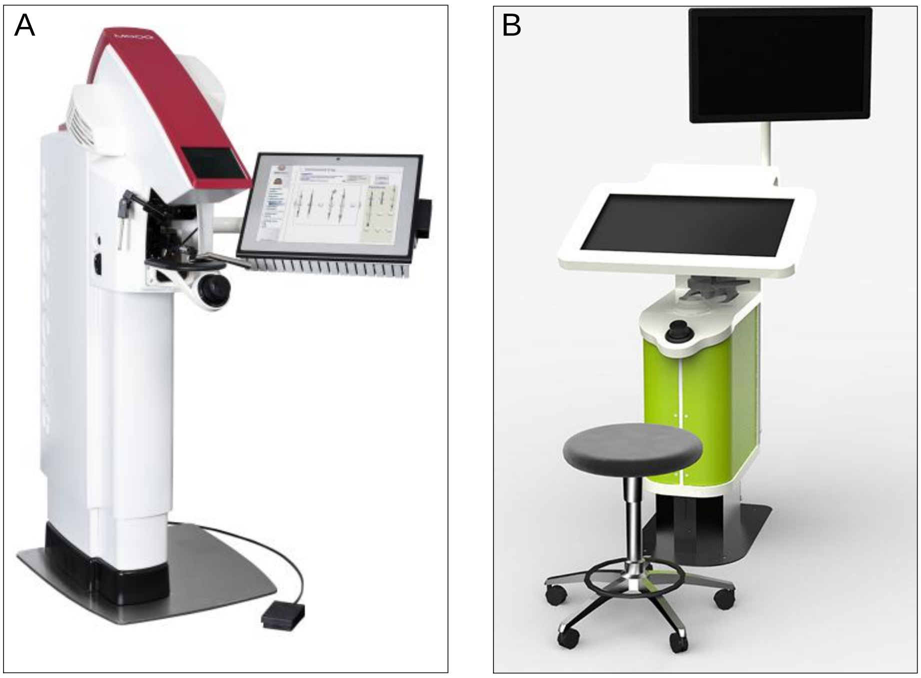

Figure 2-1 Examples of commercially available haptic VR dental simulators. [A] Simodont® (image courtesy of Moog Inc.). [B] VirTeasy® Dental simulator (image courtesy of hrv-simulation.com).

i. Simodont®

This simulator was developed by joint efforts from Moog Inc. (Nieuw-Vennep, Amsterdam, The Netherlands) a company with expertise in flight haptic simulation and ACTA (the Academic Centre for Dentistry, Amsterdam, the Netherlands).

It is the main simulator investigated in the current thesis, and in depth description of Simodont® is presented in Chapter 3 (section 3.2.1).

An early pilot study upon its introduction reported that the manual dexterity skills learned on Simodont® were transferable to a traditional, preclinical laboratory. Furthermore, the investigators observed that students working on the Simodont® had a more ergonomically correct working position than students working in phantom head laboratory; due to the fixed position of the visual display the student has to assume correct upright posture while sitting on the chair and cannot over bend his/her head while working especially while performing indirect tasks (Bakker et al. 2010). Investigation into the system continued by the researchers in ACTA (de Boer et al. 2016a; de Boer et al. 2013; Vervoorn & Wesselink 2009; de Boer et al. 2016b) and several other researchers around the world (Farah-Franco et al. 2016; Bakr et al. 2013; Koopman et al. 2010). Majority of these studies were conducted among first year dental students. The construct validity of Simodont® has been recently reported among undergraduate dental students at different levels of dental study (Mirghani et al. 2016), Simodont was found to be sensitive to variations in dental experience among participants and statistically significant differences were found between first year students and more experienced students (at year 3 onward) in performance of virtual dental tasks using the simulator.

ii. VirTeasy® dental

It is a relatively new haptic dental simulator with few evaluation and validation studies in the literature. A construct validity study was conducted by a group of researchers in France, and reported that VirTeasy® was able to discriminate between novices and experts in a restorative dentistry task (Zerbib et al. 2013). A recent study in Russia has reported its positive acceptance by dental students and its promising potential as a simulation tool for a variety of dental procedures (Abramov et al. 2016).

iii. HapTEL Project

The haptic dental simulator HapTEL (Tse et al. 2010) was developed by King's College London in collaboration with Reading and Birmingham City Universities, and involves a multidisciplinary team of experts as well as dental students. The system iterative development and evaluation process is originally focused on three main strands: technical, educational and curriculum integration (San Diego et al. 2012). The simulator allows undergraduate students to practice a number of restorative dental procedures virtually, with an interface that allows for two students as well as instructor to see the virtual tooth being prepared, in addition to a student head-tracking feature.

After eight years of research and implementation in undergraduate dental training in King's College London, the system proved its effectiveness in enhancing students' learning (Vervoorn et al. 2015). Moreover, the HapTEL system was further expanded to teach students to administer intra-muscular injections, a step that broadens the HapTEL system utility to involve other health care students (Cox et al. 2014).

In a collaborative evidence review after eight years of research, both Simodont® and HapTEL, were reported to consistently impact the students learning experience positively particularly in spatial reasoning, hand-eye coordination and fine motor skills acquisition (Vervoorn et al. 2015). Such a wide scale review highlights that there is encouraging empirical evidence that dental haptic simulators are effective, however there still exists a need for further evaluation and validation studies.

Although the current discussion is focused on VR simulators with particular applications in operative dentistry and manual dexterity training, there are other types of VR simulators that have been investigated in the literature with applications in other dental specialities. For example, dental implant training (Kusumoto et al. 2006; Chen et al. 2012), oral and maxillofacial surgery (Pohlenz et al. 2010), endodontic (Suebnukarn, Haddawy, Rhienmora, & Gajananan 2010), and periodontics (Luciano et al. 2009).

Moreover, robotic simulated patients with ultra-realistic features such as saliva secretion and various simulated movements (e.g. Dentaroid, by Nissin Inc., Japan) have been also available commercially (Nissin 2017), however, the reported evidence on their utilisation is still limited. Tanzawa et al. (2012) introduced a simulated robotic patient into a fifth year dental OSCE exam and report its effectivness in risk management skill training (Tanzawa et al. 2012). Such robotic simulated patients could potentially be used for soft skills training of undergraduate students such as patient-student communication, and patient management in various simulated scenarios.

The following section of this chapter provides an overview of virtual reality technology with focused emphasis on haptics and human interaction with VE.

2.2 Virtual Reality Technology

Virtual reality is a computer-generated 3D environment in which a user/person can interactively participate (Wann & Mon-Williams 1996) simulating various real life scenarios, especially those that are dangerous or impossible to approach physically in the real world.

Sherman and Craig (2002) defined virtual reality as " A medium composed of interactive computer simulations that sense the participant's position and actions, providing synthetic feedback to one or more senses, giving the feeling of being mentally immersed or being present in the simulation or virtual world " (Sherman & Craig 2002).

Any VR system encompasses hardware, software and assembled contents that collectively generate the VR experience (Figure 2-2).

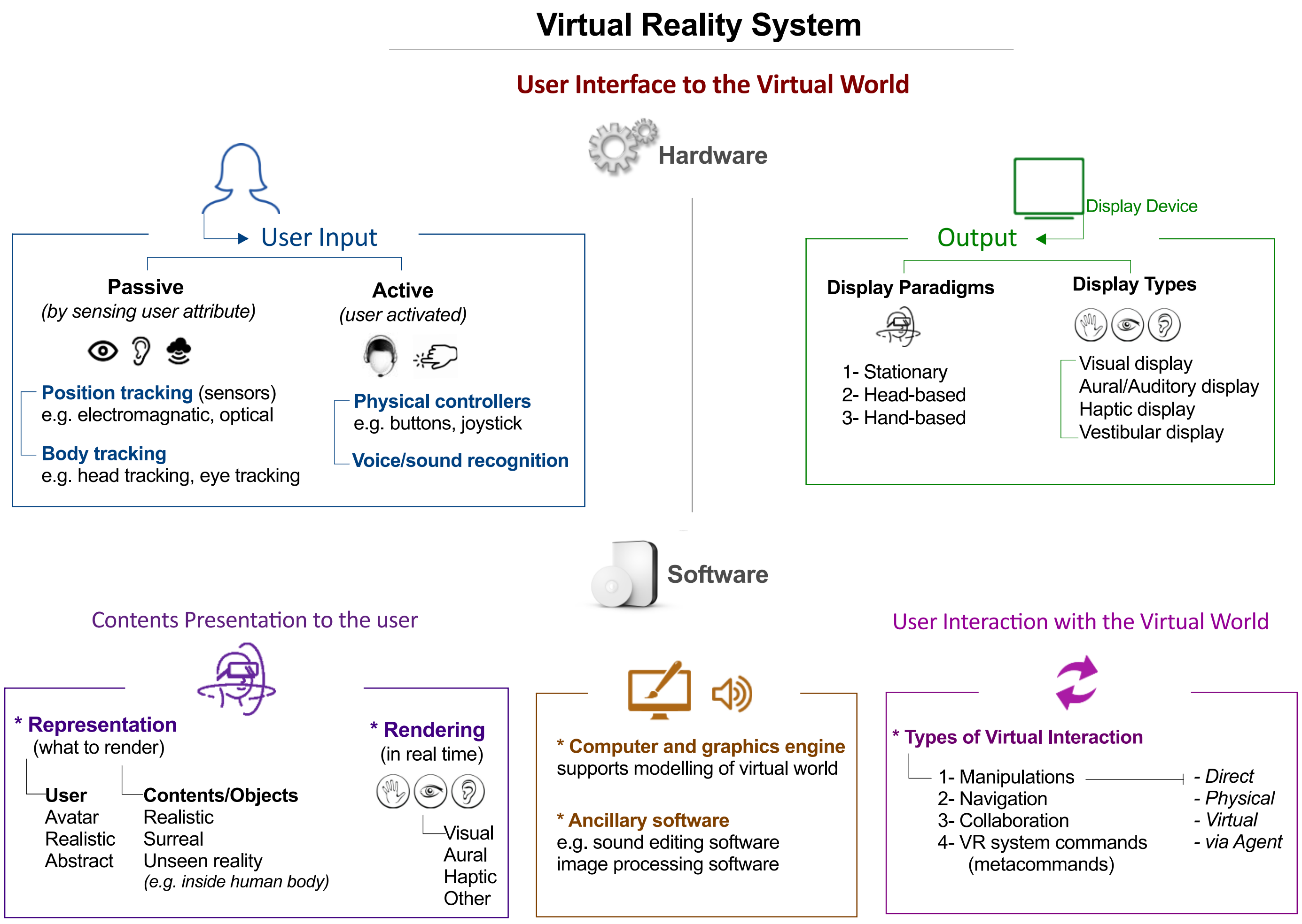

Figure 2-2 Schematic outline of the main components of Virtual Reality system. Adapted from (Sherman & Craig 2002)

Central to any VR experience are the following four key elements (Craig et al. 2009; Sherman & Craig 2002):

1- Virtual world: an imaginary space that can be displayed/modelled via special platform or medium.

2- Immersion: a sensation of being in an environment; also known as sense of presence or suspension of disbelief. It is a fundamental characteristic of VR experience. It can be physical or mental immersion achieved through synthetic stimuli to the senses via the use of technology.

3-Sensory feedback: an essential component of VR system, it determines how the virtual world is perceived by the user. In the virtual environment, synthetic stimuli are most commonly presented to all or one of the three main human perceptual senses (visual, aural, and haptic). The combined stimulation of these three senses leads to more immersion in the virtual environment. The key visual features that impact on VR display include depth perception/stereopsis, field-of-view[1], and critical fusion frequency[2] .

The sensory feedback is communicated directly to the participants based on their physical position, which must be tracked via position sensors.

High-speed computers, as mediating devices, are essential to achieve immediate interactive sensory feedback.

4- Interactivity: responding to user actions is the hallmark of the VR system. There are three forms of interactivity in the VR system:

---

[1] A measure of the angular width of a user's vision that is covered by the display at any given time (Sherman & Craig 2002).

[2] Frequency of light stimulation at which it becomes perceived as stable an continuous sensation (Critical Flickr Frequency) (Sherman & Craig 2002).

a. The ability to influence a computer-based world

b. The ability to change one's viewpoint within a world

c. The ability of the user to move physically within the world, obtaining new vantage point[3] through head movement.

2.2.1 Mixed Reality

There are many variations across what is called the "virtuality continuum" (Milgram & Kishino 1994) (Figure 2-3), ranging from completely real to completely virtual as the two ends of a spectrum. Mixed reality is the term used when real and virtual objects are used within a single display, the exact description is dependant on which platform has been used predominantly. Milgram & Kishino (1994) proposed a taxonomy of mixed reality displays based on three dimensions:

1- The extent of world knowledge (i.e. knowledge about the displayed world).

2- Reproduction fidelity (i.e. the degree of realism in the display)

3- The extent of presence metaphor (i.e. the extent of the user presence)

Augmented Reality (AR) is considered a type of virtual reality, where the virtual representations are combined with perception of the physical/real world. The user's normal vision is augmented with additional virtual information such as graphics or data that are overlaid via movable visual display (e.g. head mounted display) giving the user an altered view of the real world, and facilitate the performance of some actions that might be impossible in the real world.

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[3] A position from which something is viewed or considered.

On the other hand, Augmented Virtuality (AV) refers to a virtual environment augmented with physical elements via direct real-time interaction and representation by the user/object.

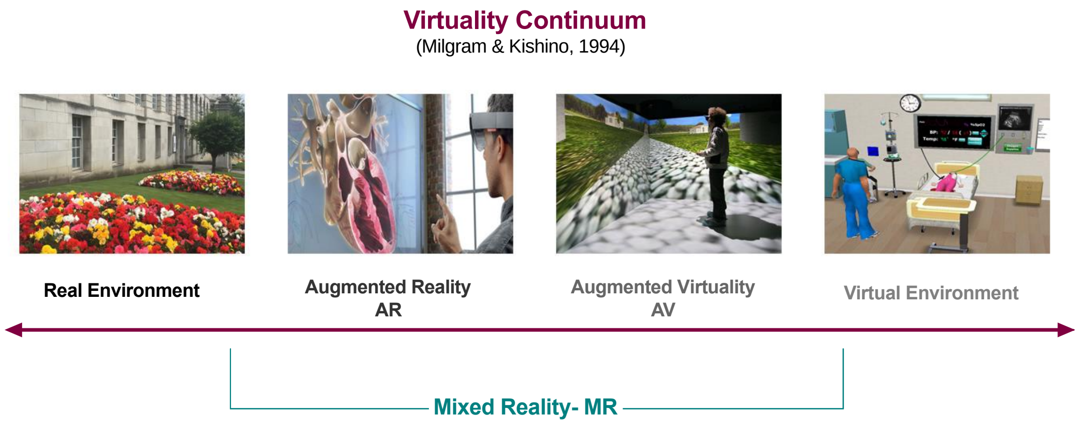

Figure 2-3 The Virtuality Continuum; adapted from Milgram & Kishino (1994). Image sources: (from real to virtual: 1-photo by the author, 2- image courtesy of microsoft hololens™:https://microsoft.com/microsoft-hololens, 3-http://antycipsimulation.com, 4- image courtesy of SecondLife® http://secondlife.com).

2.2.2 Haptics

Originally, the word haptic comes from the Greek verb (*ἅπτεσθαι*) *haptesthai: to touch*, implying the ability to touch and manipulate objects. It primarily refers to the science and physiology of the sense of touch (Grunwald 2008), however, haptics currently involve wider perspective related not only to the study of touch, but also to human-environment interaction via the sense of touch (Minogue & Jones 2006).

Haptics is a fast growing and essentially multidisciplinary field involving mechanical engineering, neuroscience, experimental psychology, robotics, and computer science with wide array of applications such as medical simulators, and rehabilitation devices.

The study of haptics is structured into three main strands: *human haptics* which involve the study of human sense of touch; *machine haptics* that involve the design and the use of devices that replace or augment human touch, and *computer haptics* that involve software for mathematical modelling and rendering algorithms for creation of virtual objects (Srinivasan & Basdogan 1997). A brief overview of each area is presented next.

2.2.2.1 Sense of Touch (human haptics)

Touch is central to the somatosensory system, which encompass networks of peripheral receptors and neural pathways connected to the central nervous system to facilitate the encoding of various sensations. Touch can be sensed across the human body via the various receptors distributed in the skin, muscles and joints. Apart from the skin, the hand - a uniquely complex organ- is considered the main part of the body that is associated with the sense of touch. The fingertips, in particular, are highly complex regions with an intense distribution of low threshold receptors, and considered one of the most sensitive areas of the human body (Vallbo & Johansson 1984; Johansson & Flanagan 2009; Grunwald 2008).

The sense of touch is mediated through cutaneous (tactile) and kinesthetic perception. The cutaneous sensory input is received via mechanoreceptors and thermoreceptors of the skin. Skin mechanoreceptors include four types (Purves et al. 2001; Grunwald 2008):

1. *Meissner's Corpuscles*: the most common type in hairless skin, and constitute about 40% of hand sensory innervation. It is sensitive to low-frequency vibrations (30–50 Hz) on the skin.
2. *Pacinian Corpuscles*: constitute about 10-15% of hand sensory innervation and detect high frequency vibrations.

3. *Markel's Disks*: constitute 25% of hand sensory innervation, particularly dense in the fingertips. They detect light pressure, object edges, and rough texture.
4. *Ruffini Corpuscles*: constitute 20% of hand sensory innervation, and detect skin stretching.

The kinesthetic sensory input is received via proprioceptors and mechanoreceptors of muscles, tendons and joints, providing information about the body position, movement and joint angle (Van Erp et al. 2010).

Haptic perception comprises both cutaneous and kinesthetic modalities and is referred to as *tactual* perception (Dahiya & Valle 2012; Lederman & Klatzky 2009).

Haptic sensorimotor loop in human and machine interactions (with real and virtual objects) is illustrated in Figure 2-4.

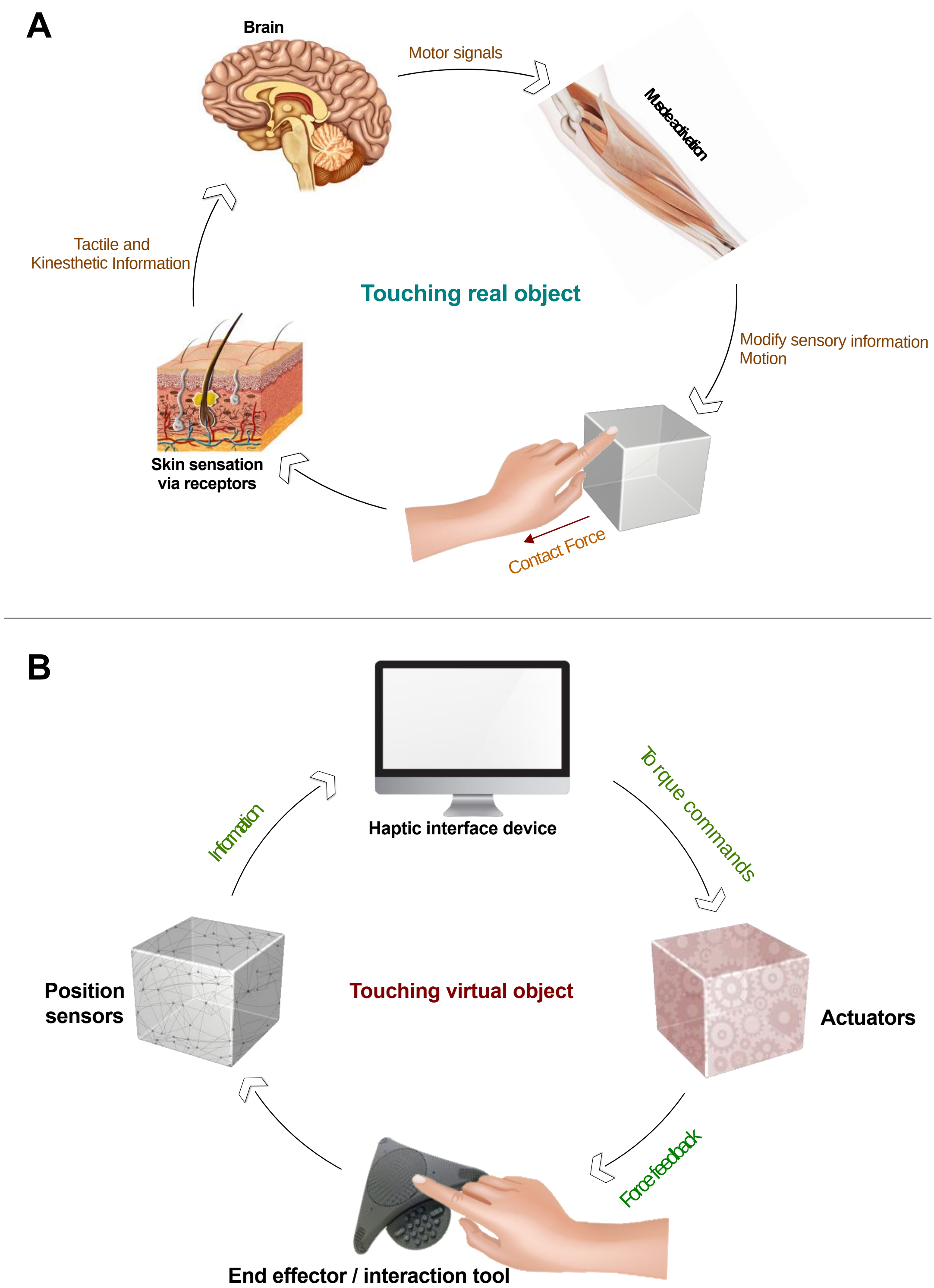

Figure 2-4 Haptic sensorimotor loops in [A] human-real object interaction and [B] human-virtual object interaction. Adapted from (Srinivasan & Basdogan 1997)

2.2.2.2 Haptic technology (machine haptics)

In computer-generated environments, the term haptics is used to describe human-machine interaction. It involves the ability to sense, manipulate and interact with virtual objects in haptic virtually simulated environment to perform specific sensory motor tasks (Srinivasan & Basdogan 1997; Mihelj & Podobnik 2012).

The haptic experience in a virtual environment (VE) is characterized by bi-directional flow of information between the user and computer-generated synthetic environment via the haptic interface that stimulates both tactile and kinaesthetic sensations by applying forces, vibration or motion to the user (Mihelj & Podobnik 2012; Robles-De-La-Torre 2009).

At a basic level, a haptic system comprises a user, a haptic interface (device), and virtual environment (VE) (Figure 2-5).

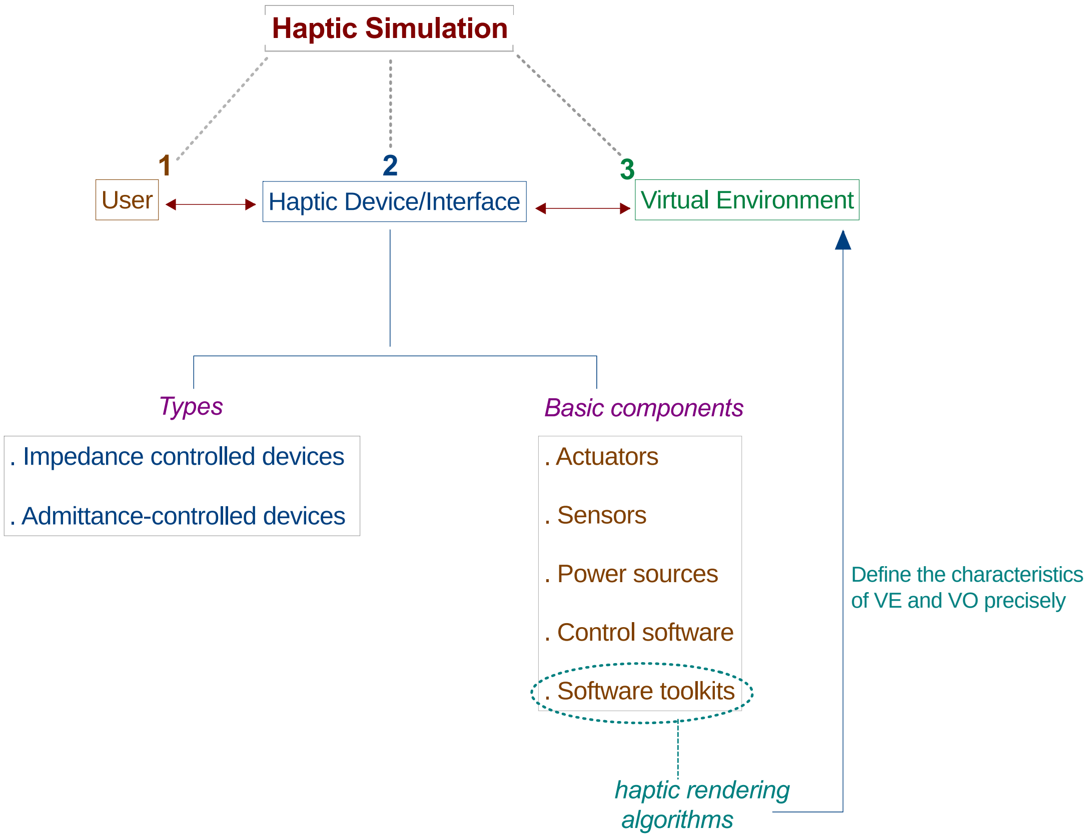

Figure 2-5 Flowchart of the basic components of haptic system.

Haptic interfaces are specialised devices (with hardware and software components) that allow user interaction with the virtual environment via realistic feel, touch and manipulation of three-dimensional objects. The mechanical components of the haptic interface are in physical contact with user who can manipulate it.

There are two basic classes of the haptic devices based on underlying control mechanism:

A. Impedance controlled devices (e.g. Sensable's Phantom devices) in which the device will react with a force if a virtual object is met via user movement (i.e. measure movement and display force; or displacement in and force out), so that the mass and friction of the device is felt by the user.

B. Admittance-controlled devices (e.g. The HapticMaster) are the opposite of impedance controlled devices, in which the device will react with the proper displacement in response to the force exerted by the user (i.e. measure force and display movement ; or force in and displacement out). Due to its robust features of high force and stiffness, the admittance control mechanism has been constantly utilized in flight simulators industry (Van der Linde et al. 2002; Mihelj & Podobnik 2012).

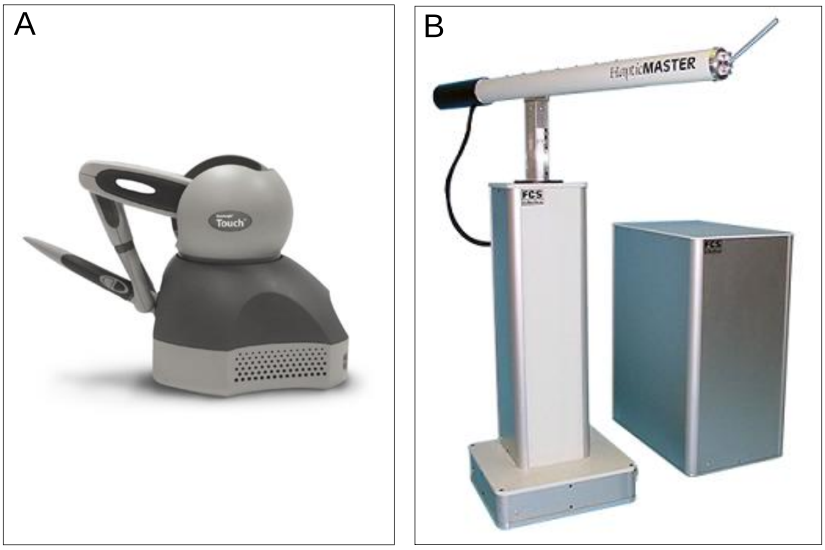

Figure 2-6 Examples of haptic devices. [A] The Geomagic Touch™ *(formerly Sensable's Phantom Omni)* an impedance controlled device by Geomagic-3D systems (image courtesy of Geomagic®: geomagic.com) *.* [B] The HapticMaster™ an admittance-controlled device by Moog FCS Robotics (image courtesy of Moog Inc.)

Haptic rendering allows the creation of 3D representation of the virtual object with a variety of characteristics (e.g. shape, surface texture and dynamics) via mathematical models that are either surface based or volumetric based models (composed of voxels). The haptic sequence of collision detection[4] and

[4] The motion of object is limited by intersections with other objects and other dynamic constrains (i.e. computational problem of detecting the intersection of two or several objects in computer simulated environment)(Srinivasan & Basdogan 1997).

response, which constitute the haptic rendering algorithm, is constantly run in real-time, and precisely defines the characteristics of the virtual environments and virtual objects (Srinivasan & Basdogan 1997; Grunwald 2008).

2.2.2.3 Haptic research in dentistry

There are two research approaches to haptics in dentistry and dental education:

1- **Haptic simulators development:** this approach focuses on the design, engineering, preliminary testing and technical specifications of simulator prototypes. The developed prototypes range in fidelity from limited haptic functionalities to more advanced prototypes that reached the stage of pilot testing with dental students and dentists (e.g. Wang et al. 2003; Wu et al. 2009; Kim et al. 2005; Yau et al. 2006; Yoshida et al. 2011).

2- **Haptic simulators utility and implementation:** this approach focuses on the investigation of the developed, or commercially available simulators including various validation studies, functional utility and comparative evaluation with the existing simulators (Luciano et al. 2009; Ben-Gal et al. 2011; Vervoorn & Wesselink 2009; Cormier et al. 2011; Tse et al. 2010).

2.2.3 Visual perception in Virtual Environment

Among the key factors that contribute to the effective use of VR simulation are human factors (ergonomics), specifically human-VR environment interaction. This form of physical and cognitive ergonomics is part of the wider concept of ergonomics that address different types of human-system interactions to ultimately optimize human well-being and overall system performance (IEA 2016). Exploring and addressing these factors will allow us to maximise VR system potential and its usability.

More specifically, there is a need to understand how students/trainees perform most effectively in VR environments. Otherwise, some issues may negatively impact on the training experience of the student, resulting in compromised learning (Lewis & Griffin 1997) and negative transfer of training[5].

The existing body of literature on human factors in VR environments has focused on several aspects such as human performance efficiency and systems characteristics, in addition to health and safety issues. Human performance efficiency in VE is affected, among other factors, by the individual user differences that can be simplified (Stanney et al. 1998) as differences in:

1. Input (the user/student perception in VE) e.g. visual depth perception, and Inter pupillary distance (IPD).
2. Throughput (how the user/student interpret the received information) e.g. cognitive styles.
3. Output (how the user/student interact and perform the desired task) e.g. task performance.

[5] Negative transfer occur if the practiced task impaired the performance of subsequent task or negatively affecting its performance (Schmidt & Wrisberg 2008).

Visual perception parameters particularly depth perception and stereopsis are important user factors that influence the performance on VR 3D simulators with stereoscopic displays. Therefore, understanding depth perception mechanisms is central to successful performance in virtual environments (Poyade et al. 2009).

2.2.3.1 Depth perception

Depth perception is not a single entity but rather a complex process that comprises rich sensory information conveyed to the brain and influences the quality of human-environment interaction and performance of everyday tasks (Blavier & Nyssen 2008) via various types of retinal and extra-retinal cues.

- *The extra-retinal (oculomotor) depth cues* are provided by the eye muscles proprioception and include accommodation[6] and convergence[7].
- *Retinal (visual) depth cues* include binocular and monocular cues.

The horizontal separation of the human eyes, which is known as the average inter-ocular distance (ranges from 6.3 cm to 6.5 cm), results in two slightly different retinal images presented to each eye (binocular disparity) and fused by the brain to give the perception of depth in its highest form to visualize objects in three dimensions. Binocular and oculomotor cues play a major role in depth perception at near distance (within 3m) (Lin & Woldegiorgis 2015). The perception of the third dimension is further enhanced by coordinating the gaze direction of both eyes, as well as by motion (via head, body and object movements). It is noteworthy that each type of movement generates different

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[6] The eye ability to change its focus from distant to near object via adjusting the focal length of the lens.

[7] The simultaneous inward movement of both eyes toward each other.

three dimensional information which is also different from 3D information derived from a stationary position (Wexler & van Boxtel 2005).

At the neuronal level, the perception of stereoscopic depth is a multi-stage process involving dorsal and ventral cortical pathways (Parker 2007).

Monocular cues can be obtained by one eye only and perceived in just two dimensions. Examples of monocular depth cues include occlusion, linear perspective, motion parallax, texture, size, and shading and contour (Poyade et al. 2009; Bruce et al. 2003). These cues can be also described as relative cues, which indicate how far an object is from the observer relative to another object. On the other hand, accommodation and convergence cues are described as egocentric cues, which give information about the distance between the observer and an object (Hofmeister et al. 2001).

The brain uses a combination of different depth cues to achieve precise and reliable perception of the surrounding world (Lambooij et al. 2009). Although depth can be perceived with monocular cues only, the finest quality and vividness of depth (or the relative z-axis) can be only perceived with binocular disparity (known as stereopsis) which is the most accurate among other depth cues (Poggio & Poggio 1984; Fielder & Moseley 1996; Saladin 2005). Generally, the availability of depth cues, particularly stereopsis, significantly affect the hand-eye coordination which is most useful in the fine tuning of motor control tasks (Schiller et al. 2012).

The last section of this chapter provides an overview of the principles of motor learning as an integral component in understanding skill acquisition in real and simulated environments.

2.3 Principles of Motor skill learning

2.3.1 Motor skill

Motor skill can be defined as an activity that requires voluntary movement of the head, body, and/or limbs to achieve a specific goal with a level of proficiency. Fine motor skill is a type of motor skill that utilizes small musculature as the primary muscles involved in performance to achieve a specific goal that needs hand-eye coordination, and a high degree of precision of hand and fingers movement (Magill 2011).

Any motor skill encompasses a subset of motor abilities, which are individual traits that collectively form the basis for skill performance. These abilities determine the person performance potential to be skilful at certain motor tasks (Haibach et al. 2011). It follows that the individual differences (i.e. strength level, and limitations) in the underlying motor abilities impact their potential and achievements for skilled performance. Moreover, the pattern of motor abilities that underpin skilled performance can be modified with practice (Schmidt & Wrisberg 2008).

The specificity hypothesis indicates that each motor skill requires very specific motor abilities for skilled performance, a unique combination of several abilities (Henry 1968; Haibach et al. 2011). According to Fleishman (1975) and based on many research studies, abilities can be categorized into perceptual–motor abilities (related more to fine motor skills) and physical proficiency abilities (related more to gross motor abilities). From Fleishman’s taxonomy (Fleishman 1975), we can identify the perceptual-motor abilities that are directly related to dentistry and dental performance and these are presented in Table 2.3-a.

Table 2.3-a Perceptual-motor abilities directly relevant to dentistry and dental performance (Fleishman 1975; Magill 2011).

Perceptual motor ability	**Definition**	**Example**
Control Precision	Ability to make rapid and precise movement adjustments of control devices involving single arm-hand movements.	° Manipulating the handpiece during cavity preparation.
Manual dexterity	Ability to make skillful arm-hand movements to manipulate objects under speed conditions.	° Cementation of anterior esthetic porcelain veneers
Finger dexterity	Ability to make skillful, controlled manipulations of tiny objects involving primarily the fingers.	° Carving amalgam restoration ° Applying resin composite layered restoration
Arm-hand steadiness	Ability to make precise arm-hand positioning movements where strength and speed are minimized. It includes steadiness maintenance during arm movement or static arm position.	° Moving the handpiece to prepare a full crown (indirectly) in a maxillary molar tooth
Wrist, finger speed	Ability to make rapid and repetitive movements with hand and fingers, and/or rotary wrist movements.	° Applying Tofflemire matrix band ° Cleaning and shaping of root canal with rotary files
Aiming	Ability to rapidly and accurately move the hand to small target.	° Applying pulp capping material ° Caries excavation

2.3.2 Motor learning

Motor learning is defined as "*a set of complex processes (perception, cognition and action) associated with practise or experience, leading to relatively permanent changes in the capability of producing skilled action*" (Shumway-Cook & Woollacott 2012). Motor learning can involve the acquisition of new motor skill, performance enhancement of a learned skill, or the re-acquisition of motor skill that has been affected by disease or injury (Magill 2011). In dentistry, learning fine motor skills can involve all the three mentioned types at different stages, for example, the preclinical stage is primarily dedicated to the acquisition of new skills; clinical and post graduate stages are mainly focused on enhancement of the learned skills, although new motor skills can be learned at anytime during dental career.

On the other hand, motor control is related to the regulation of the motor activity through neuromuscular coordination and activation of specific body parts involved in the skilled action (Magill 2011).

Early theories of motor skill acquisition (e.g. Anderson (1982), Fitts and Posner (1967), and Schneider and Shiffrin (1977)) characterize learning as a multi-stage process based on cognitive demands perspective that starts with conscious effort and reliance on resources to perform a motor task and culminates in performance independence or automaticity (Langan-Fox et al. 2002). In Fitts and Posner's (1967) theory it was proposed that motor skill acquisition follows three stages. The cognitive stage involves a high degree of cognitive activity, such as understanding the nature of the task and develop strategies to carry out the task. Next is the associative stage, in which the learner begins to refine the learned skill, with improved error detection and correction mechanisms. The third stage is the autonomous stage in which the skill becomes automated with less cognitive demands during its performance (Shumway-Cook & Woollacott, 2012).

More recently, researchers have suggested that the motor learning process can be explained as (Wolpert et al. 2011) : motor learning components (task-relevant information), the processes involved in learning these components, and the internal representation of motor learning (internal models). Those recent concepts are presented in a simplified flowchart (Figure 2-7) that categorize the principles of motor learning into three main parts: what are the components of motor learning, how to learn these components, and where the learning is represented in our brain (internal neural models).

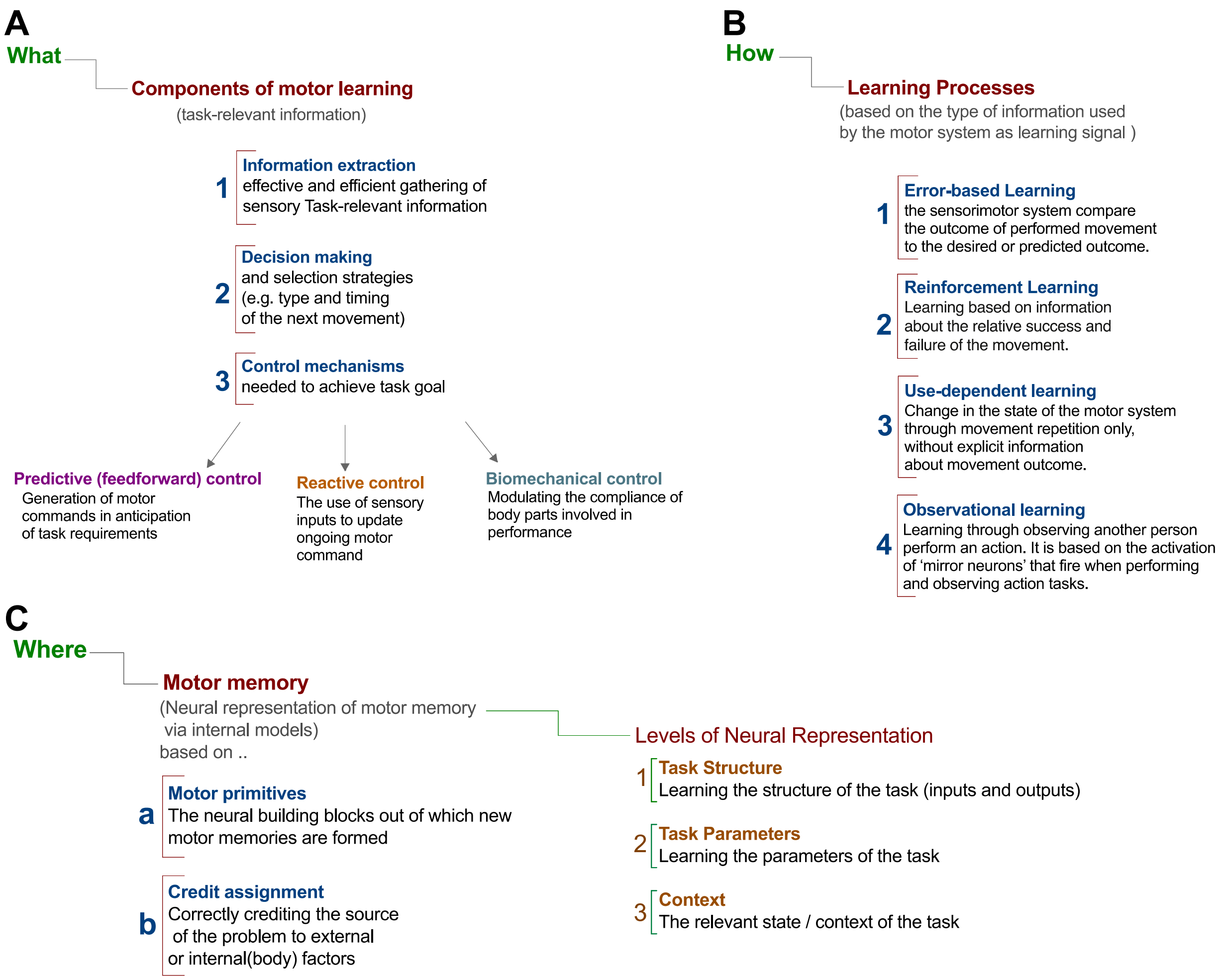

Figure 2-7 Simplified flowchart of the principles of motor learning; based on Wolpert et al. papers (Wolpert et al. 2011; Wolpert & Flanagan 2010)

2.3.3 Motor Learning and performance

Performance is differentiated from learning as being a transitory change in motor action during practice, which can be observed and measured. Learning is a relatively permanent change that can not be directly measured but can be inferred and evaluated after practice by identifying specific performance characteristics namely improvement, consistency, stability, persistence and adaptability. Retention test for example is a mean of evaluating performance persistence while transfer test is evaluating the adaptability of the performance to novel context (Magill 2011; Shumway-Cook et al. 2012). The goal of dental training is not only to facilitate performance during practice, but also to enhance the skills learning and transfer.

Generally, three main factors influence the performance of any motor skill: the skill characteristic, the person who performs the skill, and the performance environment (context).

Sensorimotor learning can be measured through its behavioural effects. Improvement of motor task performance may occur with repeated practise over time, which could be as a result of learning or some other factors such as increased motivation. To determine if the improvement is an actual learning effect, a retention test can be performed after the initial skill-training phase. The rationale is to allow time for other intervening factors (e.g. fatigue and motivation) to fade or return to normal. Therefore, the retention test provides a measure of the extent to which improvements made during the training phase are retained over the interval between training phase and retention test (Tresilian 2012).

Skill retention depends on the type of skill acquired, the extent of skill learning and the time interval between training and re-test (retention test) (McGaghie et al. 2010).

The variability of performance during training can be used as a measure of learning; if the skill is being learned, the variability in performance should decrease and the overall performance becomes more consistent. Haptic feedback in virtual reality simulations can enhance the psychomotor skill learning by reduction of the learning time (shorter learning curve), improvement of performance quality and dexterity in a realistic virtual environment (O'Malley et al., 2006).

Among several factors that influence the motor skill learning and performance, some are particularly relevant to medical and dental training. Wulf et al. (2010) identified four factors, described next, that have consistently been shown to enhance the motor skill learning including: observational learning, learners' focus of attention, performance feedback and self-controlled practice (Wulf et al. 2010).

A- **Observational learning:** evidence from neuroimaging research indicates the importance of observational learning (Gallese & Goldman 1998; Molenberghs et al. 2012). It shows that during action production and observation a set of specific neural structures are activated. The unique contribution of observation to motor learning is that it allows the learner to process information (related to coordination patterns and subtle task features and evaluate task strategies) that would be impossible to process during physical practice.

   It has been shown that alternating between physical practice and observation (e.g. dyad practice[1]) contributes positively to performance during retention and transfer. This has an implication in increasing the efficiency of training without increasing the time or the need for extra resources.

B- **Focus of attention:** it has been shown that during motor skill instruction, when the trainee attention is directed toward body parts (e.g., hand, fingers) the learning was relatively ineffective, compared to directing the trainee's attention to external focus (e.g. site of carious lesion). The external focus of attention results in more efficient learning by speeding up the early phases of motor learning, and minimizing self-focus that may detract from the concentration on critical performance components. Therefore, simple verbal change during motor skill instruction can significantly influence performance outcome. This particularly impacts the learning of complex motor skills that need high levels of coordination.

This area of research is still evolving with more yet to be learned about what optimal external foci would enhance the learning of specific motor skills.

C- **Feedback:** it is one of the most influential factors affecting motor skill learning. Evidence suggests that not only the informational component of feedback is important in motor skill learning but also the motivational components as well.

A more detailed discussion about the role of feedback in motor skill learning is presented in Chapter 6 of this thesis.

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[1] Two participants alternate between physical and observational practice, undertaking only half of the training physically compared to individual training (Wulf et al. 2010).

- **D- Self-controlled practice:** evidence from motor learning literature suggests that learning of a motor skill is enhanced when learners are given a degree of control/ autonomy over the practice conditions (e.g. practice schedule, timing of feedback) (Zimmerman 2002). This changes the learner’s passive role in a prescribed practice protocol, to active involvement, participation and motivation.

2.3.4 Performance measures

As mentioned above, motor learning cannot be measured directly, it can only be inferred from characteristics of a person’s performance. The measurement of motor performance is categorised into outcome & production measures. Outcome measures indicate the performance outcome of a motor skill (e.g. percentage of errors). Performance production measures relate to the characteristics that produced the outcome, it indicates specific aspects of the motor control system during action performance (e.g. displacement, velocity) (Magill 2011; Tresilian 2012). Error measures are important and meaningful performance outcome measures particularly with fine motor skills that demand precision and accuracy. Error measures can indicate the causes of performance problems, which is essential for motor learning and for instruction as well (Magill 2011). Kinematic measures are performance production measures that are based on recording the movement of specific body parts while a person is performing a skill. Kinematic is a descriptive term that refers to motion without regard to forces or mass, when the force is considered it is referred to as Kinetics. Kinematic measures denotes three characteristics: displacement, velocity and acceleration (Magill 2011).

A haptic VR system can provide error and kinematic measurements automatically which can be used for objective assessment of task performance. Such data are not available in conventional skill training environments (Suebnukarn et al. 2009).

Chapter 3 : Face and content validity of Simodont® virtual reality haptic dental simulator

Virtual reality simulators have been increasingly adopted in undergraduate dental education (Dutã et al. 2011; Perry et al. 2015). The growing body of literature on the utility of various types of VR simulators in dental education is promising and starting to substantially impact the pedagogical approach to undergraduate dentistry (Buchanan 2004; Wierinck et al. 2007; Rees et al. 2007; Bakr et al. 2013; Vervoorn et al. 2015; Cox et al. 2015). The increased availability of dental virtual reality simulators demand a thorough evaluation of their features in order to facilitate a well informed decision process about how to best utilize and integrate them into the dental curriculum. The evaluation of these simulators is a multistep process that starts by investigating the perception of the new technology by the primary users (educators, and students at different stages) and validation of its various contents and potential utility. Therefore, validation of virtual reality simulator is a vital first step before its full adoption (McDougall 2007).

Validity refers to the ability of a test/device to measures what it is intended to measure, (i.e. the simulator actually measures what it is intended to evaluate or measure). Benchmarks have been developed for validity assessment using several methods including face validity, content validity, concurrent validity, construct and predictive validity. Face validity relates to the realism of the simulator, while content validity evaluates the training potential of the simulator as a teaching modality. Both face and content validity relies on expert judgment during the early phases of simulator introduction (McDougall 2007; Gallagher et al. 2003).

The term simulator realism is frequently used to describe how closely the features, appearance and functionality of the simulator resemble real-world conditions that are being simulated (Maran & Glavin 2003; Hamstra et al. 2014). It is mainly referring to the simulated design features that look-like the features of the real case (e.g. plastic typodont tooth closely representing the natural tooth shape, anatomic features and color). There are wide variations in the degree of simulator realism from sophisticated replication of full real-life features to simplified representation of some aspects of the case/task . The term fidelity is sometimes used to broadly describe the simulator realism. However, simulation fidelity encompasses two specific elements, the structural and the functional fidelity. The structural fidelity is related to the realism of the simulator appearance, while the functional fidelity is related to how closely it simulates the target action. Structural fidelity/realism does not necessarily translate into educational effectiveness and the extent of simulator fidelity should be mapped strategically into the learning objective of the specific training context (Hamstra et al. 2014).

The Simodont® is one currently available haptic VR dental simulator. The realism of the simulator has been evaluated, upon its first introduction, among 10 educators and 25 general dental practitioners (Vervoorn & Wesselink 2009). Subsequently, its realism and the training potential were evaluated by researchers from Griffith university in a series of three studies, one among 11 academic staff (Bakr et al. 2013) , among second year dental students (Bakr et al. 2014), and among 4th and 5th year dental students (Bakr et al. 2015). More recently, the Simodont® user experiences among 68 first year dental students have been also evaluated (Farah-Franco et al. 2016). Although face validity has been established among undergraduate dental students in the previously mentioned studies, there have been no reported face and content validation studies, so far, among postgraduate dentists from different dental specialities.

This group has diverse educational and clinical background that will enrich the available data regarding various user experiences, and will contribute to face and content validation literature of Simodont®, which should ideally inform the future utility and design of this simulator.

3.1 Aim

The current investigation aimed to explore, via a post experience online questionnaire, the face and content validity of Simodont® haptic dental simulator among a group of postgraduate dental students with at least 3 years dental experience, following their participation in a study using the Simodont® simulator (Chapter 5, section 5.2).

3.2 Methods

3.2.1 Simodont® haptic dental simulator

The Moog Simodont® dental trainer is a virtual reality haptic dental simulator developed by Moog Inc. (Nieuw-Vennep, Amsterdam, Netherlands) and ACTA (the Academic Centre for Dentistry, Amsterdam, the Netherlands). The Simodont® device consists of a training console with haptic interface and an attached computer screen.

3.2.1.1 The haptic interface

The key feature of any haptic interface is that it allows user interaction with the virtual environment via simulated sensory information and force feedback that allow touch and manipulation of three-dimensional objects.

Simodont's® haptic interface provides force feedback based on the admittance control paradigm (for details see page 32,33) of the HapticMaster (Moog Inc. 2011) (Figure 2-6,B), through which the simulator responds to force exerted by the user, leading to a sense that the user is interacting with an object of equal mass.

The simulator comprises of two separate, varied frequency loops (haptic and graphics). The simulation of tooth cutting and collision detection runs via the haptic loop so that the realistic force feedback in tooth cutting simulation is computed within 1 millisecond. The force feedback robotic arm is connected to the courseware so that every movement is visualised on the attached computer screen (Bakker et al. 2010).

3.2.1.2 Simulator Screen

The training console of the simulator consists of a small screen (5” size with a 60Hz refresh rate and 800x600 resolution) located in front of the trainee so that it simulates the patients’ head position. Underneath the screen is a physical handpiece with a virtual tip, and dental mirror handle with virtual head. The screen size is ‘life-sized’ and accurately seen in the physical workspace of the hand piece, which is mirrored in the co-located visual display (Moog Inc. 2016). The high-resolution stereo image with real size co-located visual display (approximating the human eye acuity limits) is facilitated by 3D projection and mirror technology. Magnification (zoom in/out) of the 3D display is possible up to 125% in the current settings used with all participants in our studies, but can be increased up to 300%, similarly, the full rotation of the virtual models in the 3D display is possible.

3.2.1.3 Stereoscopic display

To obtain the 3D stereoscopic vision in Simodont®, the simulator is equipped with two digital multimedia projectors from LG™ (type HS101, resolution 800X600), which operate simultaneously resulting in projection of two images superimposed onto the screen through a polarizing filter. The operator needs to wear passive polarised glasses for the image to be perceived as one 3D image (de Boer et al. 2016a).

For the 2D vision in Simodont®, one of the projectors can be turned off, and in our stereopsis experiment (Chapter 5, section 5.2) we asked the participants to wear another type of glasses (non polarized lightly tinted glasses) to perform the tasks under 2D conditions. The simulator was engineered to output a single image (to both eyes) within the non-stereoscopic conditions.

3.2.1.4 Courseware

A separate computer is attached to the Simodont® training console and it contains a specialised courseware (developed by ACTA), with two components: the virtual clinic and the virtual lab.

The courseware comprises lesson programs and modules with a range of manual dexterity exercises, operative dentistry procedures, as well as crown and bridge cases, all with varied levels of difficulty. The manual dexterity module offers automatic evaluation and records the real-time kinematics of student performance, which appears on the attached computer screen and shows all the recorded metrics in detail (e.g. the percentage of the target removed, the percentage of errors done to the sides and bottom of the shape). Therefore, the participant will be able to monitor his/her progress in real-time. The available teeth library is derived from real extracted teeth. The volumetric data of the teeth is acquired via i-CAT™ scanner - a specialised cone beam Computed Tomography technology for dental CT scans (Imaging Sciences International, LLC) (Bakker et al. 2010). The varied force feedback of the virtual teeth is based on the density values of the manipulated dental tissue;

for example enamel is harder to remove than soft carious dentin. The virtual teeth library is expandable and editable, allowing for the addition of various shapes and sizes of virtual teeth with and without pathology (de Boer et al. 2013), with unlimited practice possibilities using imported dental cases of varied complexity, contributed by some dental schools including ACTA and Leeds School of Dentistry (Moog Inc. 2016).

3.2.1.5 Virtual handpiece and instruments

Hand instruments are simulated (true to size) as well as various types of dental bur (diamond, tungsten carbide and steel). Dental mirror allows the realistic examination of the teeth from all sides, in addition to other instruments such as dental explorer with force feedback. The dental tools have six degrees of freedom positional sensing, generating three degrees of freedom force feedback (Bakker et al. 2010).

The speed of the virtual hand piece is controlled using a realistic foot pedal. Once the operator presses the foot pedal the handpiece operates with a realistic air turbine (rotor) sound and the dental bur starts revolving. Once the bur comes in contact with the block or the virtual tooth the cutting takes place providing that the participant presses on a specific area of the virtual tooth. When a virtual tooth is cut, multimodal simultaneous visual, audio and tactile feedback are received (de Boer et al. 2013).

Figure 3-1 Simodont® simulator device with labelled components. Image courtesy of Moog (Moog Inc. 2011).

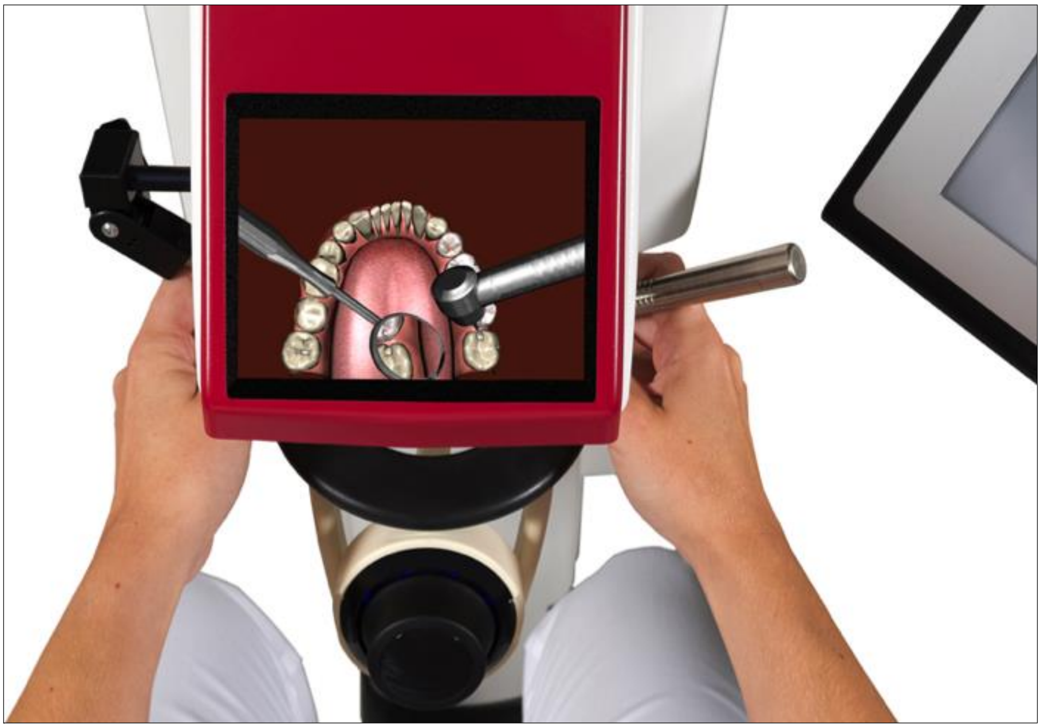


Figure 3-2 Simodont® trainee perspective showing the co-located visual display as the screen appears in the physical workspace of the handpiece and the mirror. Image courtesy of Moog (Moog Inc. 2011).

3.2.2 Participants

Sixteen participants (13 female and 3 male, mean age = 32.8 years, *SD* = 3.5 years) participated voluntarily and answered the questionnaire after completing the stereopsis experiment using Simodont® haptic simulator (Chapter 5, section 5.2) . The participants were postgraduate dental students, from various dental specialities with at least three years of clinical experience (Figure 3-3), completing their studies at the School of Dentistry, University of Leeds. They had no previous experience in using Simodont® or any other dental VR simulator. Ethical approval was obtained from DREC (Dental Research Ethics Committee) at the School of Dentistry, University of Leeds (DREC ref: 230915/LA/178).

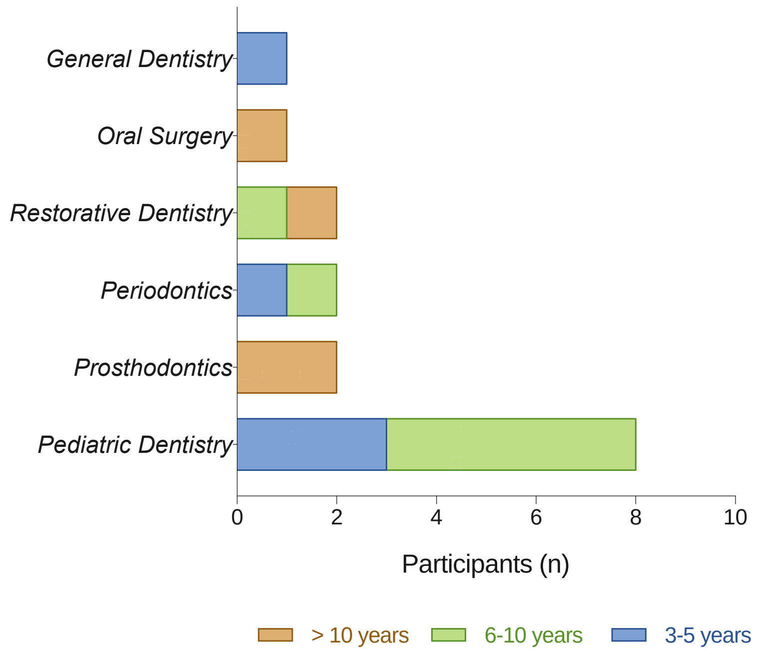


Figure 3-3 The participants' (N=16) dental speciality and clinical experience by years of dental practice.

3.2.3 Questionnaire

An online questionnaire (appendix A.1) was sent via email link to all participants, after the stereopsis experiment, to explore the Simodont® user experience. The questionnaire is structured into the following 4 main sections with a total of 30 questions:

A. Section A (4 questions) focused on general demographics (age, gender, dental specialty, years of dental practice).

B. Section B (10 questions) focused on face validity/ simulator realism (visual realism, auditory realism, haptic realism, the 3D representation). The questions in this section were on a 5-point Likert scale: (1-Very realistic, 2-Realistic, 3-Neutral, 4-Not realistic, 5-Not realistic at all).

C. Section C (16 questions) focused on content validity / simulator usability and training potential. The questions in this section were on a 6-point Likert scale: (1-Strongly disagree, 2-Disagree, 3-Neither agree nor disagree, 4-Agree, 5-Strongly agree, 6-do not know).

D. Free text comment space was provided for feedback and elaboration on the experience of using Simodont® and any additional issues that were not covered in sections B and C.

The questionnaire was pilot tested with postgraduate colleagues in dentistry, not involved in the experiment, for wording and overall consistency and it was refined accordingly.

3.2.4 Statistical data Analysis

Descriptive statistics, frequency distribution and statistical comparisons for all ratings were determined. Combined ratings were calculated to obtain the overall experience as positive, neutral, or negative: For section B: positive (Very realistic and Realistic), neutral and negative (Not realistic and Not realistic at all). For section C and sub-sections: yes (Agree and Strongly agree), neutral (Neither agree nor disagree and do not know) and no (Strongly disagree and Disagree). To explore group differences based on specialism, Kruskal-Wallis H test was conducted for each item in section B and C of the questionnaire. All statistical analyses were performed using IBM SPSS® Statistics for Windows (Version 22, Armonk, NY: IBM Corp., 2013). The free text comments were analysed and coded into main themes.

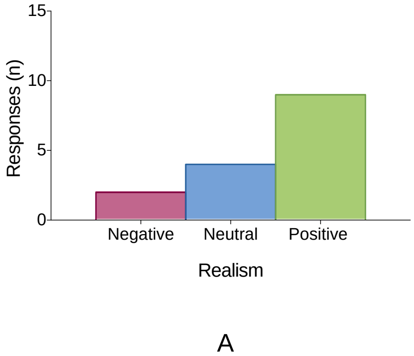
3.3 Results

3.3.1 Reliability

Cronbach's alpha was calculated to test reliability and internal consistency for the ratings of section B (simulator realism) and section C (training potential) of the questionnaire. Both sections had a high level of internal consistency, with Cronbach's alpha values of (.806) for section B and (.755) for section C.

3.3.2 Responses for simulator realism- *section B*

The realism of the simulator was investigated in 10 questions, and the results showed that postgraduate dentists generally viewed the Simodont® as realistic tool (Figure 3-4). The means for each question and frequency distribution of the ratings is presented in (Table 3.3-a).



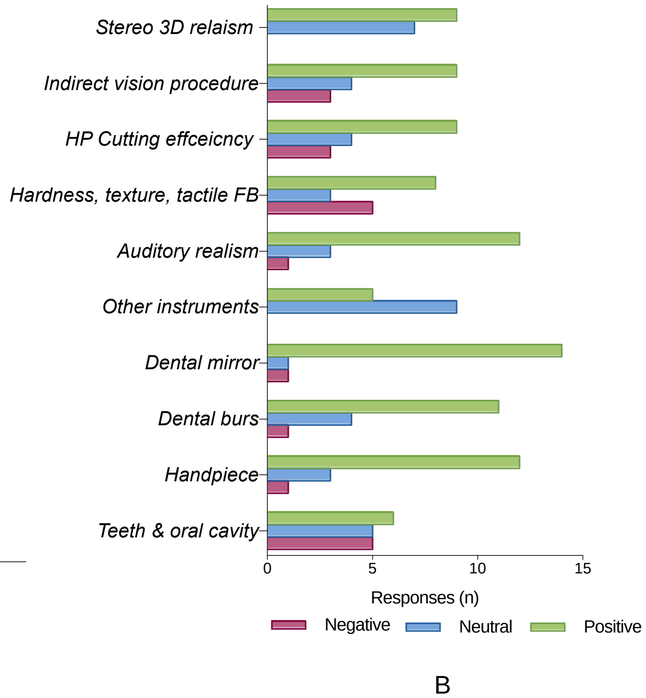


Figure 3-4 Combined overall ratings for the Simodont® realism [A] in general and [B] for each item in section B (realism).

Table 3.3-a Means (±*SD*), variance, and frequency distribution of section B of the questionnaire (face validity), on 5-point Likert scale (1:Very realistic, 2:Realistic, 3:Neutral, 4:Not realistic 5:Not realistic at all)

Question	Mean (SD)	Variance	1 n(%)	2 n(%)	3 n(%)	4 n(%)	5 n(%)
Visual realism							
Teeth (and oral environment)	2.94(± 0. 854)	0.729	0	6 (37.5%)	5 (31.3%)	5 (31.3%)	0
Handpiece	2.19(± 0. 750)	0.563	2 (12.5%)	10 (62.5%)	3 (18.8%)	1 (6.3%)	0
Dental burs	2.25(± 0. 775)	0.600	2 (12.5)	9 (56.3%)	4 (25%)	1 (6.3%)	0
Dental mirror	2(± 0. 73)	0.533	3 (18.8%)	11 (68.8%)	1 (6.3%)	1 (6.3%)	0
Other instruments	2.64(± 0. 497)	0.247	0	5 (31.3%)	9 (56.3%)	0	0
The indirect vision (mirror vision) exercise	2.44(±1.21)	1.463	4 (25%)	5 (31.3%)	4 (25%)	2 (12.5%)	1 (6.3%)
Haptic realism							
Hardness, texture and tactile feedback of enamel, sound dentin and carious dentin	2.88(±1.025)	1.05	0	8 (50%)	3 (18.8%)	4 (25%)	1 (6.3%)
The cutting efficiency of the handpiece, manipulation of the instruments (excavator, probe etc.)	2.5(± 0. 966)	0.933	2 (12.5%)	7 (43.8%)	4 (25%)	3 (18.8%)	0
Auditory realism							
The sound of the handpiece	2(± 0. 894)	0.800	5 (31.3%)	7 (43.8%)	3 (18.8%)	1 (6.3%)	0
Stereoscopic realism							
The depth of the virtual scenery (the 3D representation)	2.38(± 0. 619)	0.383	1 (6.3%)	8 (50%)	7 (43.8%)	0	0

3.3.3 Responses for simulator training potential - *section C*

The training potential of the simulator was tested through 16 questions in Section C of the questionnaire. Generally, the participants believe that Simodont® is a valuable training tool to supplement, but not to replace, existing phantom head simulator (Figure 3-5). The participants believe that Simodont® is not difficult to use (Figure 3-6A) and they positively rated the indirect vision exercise (Figure 3-6B) as well as their overall Simodont® experience (Figure 3-6C). The mean for each question and frequency distribution of the ratings is presented in (**Table 3.3-b**).

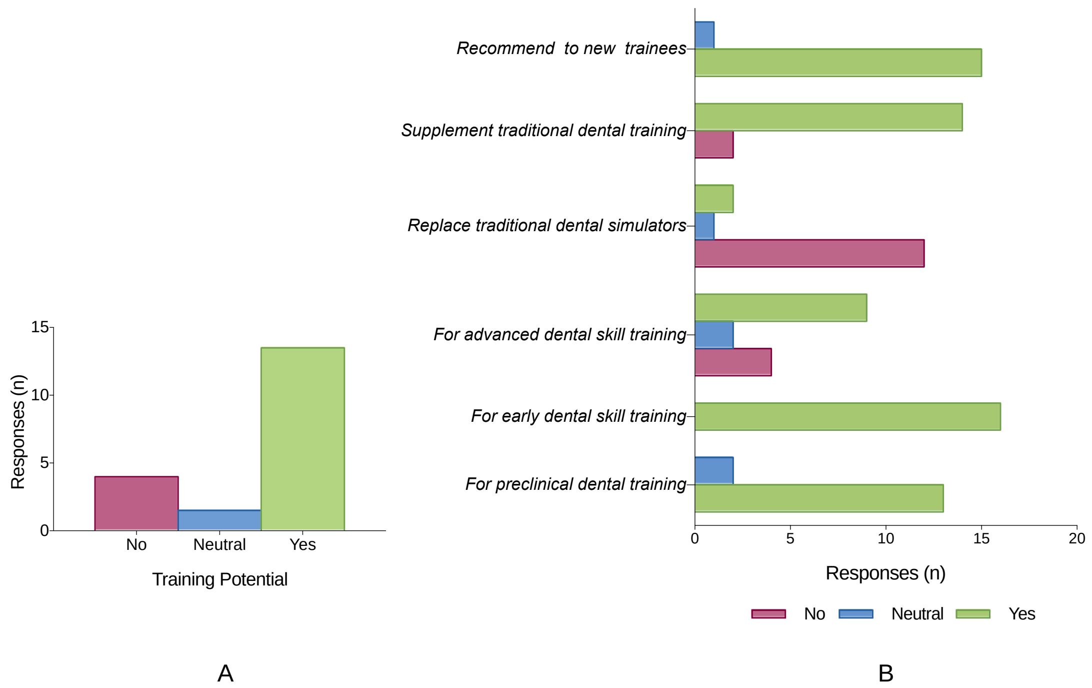


Figure 3-5 Combined overall ratings for the Simodont® training potential [A] in general and [B] for each item in the sub-section.

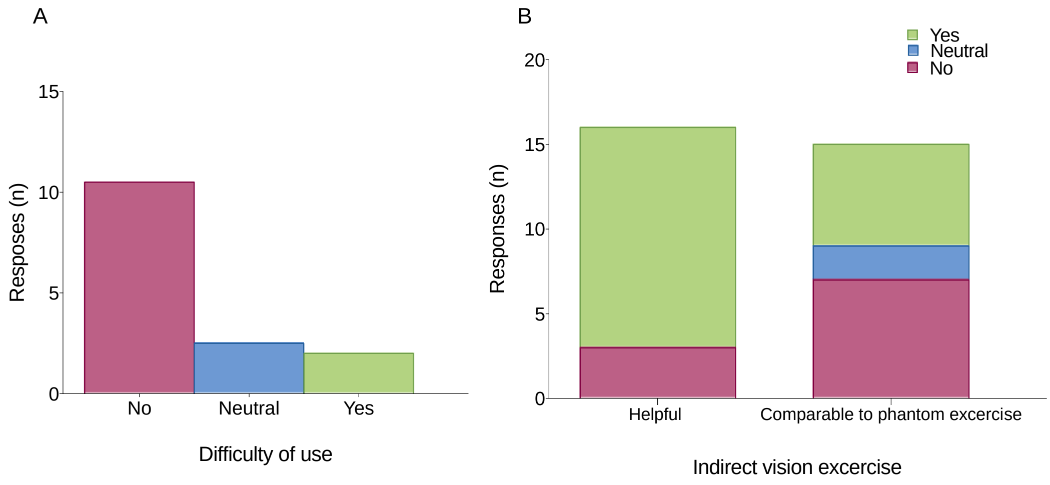


Figure 3-6 Combined overall ratings for the Simodont® [A] difficulty of use; and [B] indirect vision exercise subsections of the questionnaire section C.

Table 3.3-b Means (±*SD*), variance, and frequency distribution of section C of the questionnaire (content validity), on 6-point Likert scale (1:Strongly disagree, 2:Disagree, 3:Neither agree nor disagree, 4:Agree, 5:Strongly agree, 6: do not know)

Question	Mean (SD)	Variance	1 n(%)	2 n(%)	3 n(%)	4 n(%)	5 n(%)	6 n(%)
Difficulty of use								
I found the simulator unnecessarily complex	2 (± 0.73)	0.533	3 (18.8%)	11 (68.8%)	1 (6.3%)	1 (6.3%)		
The simulator was difficult to use	2.25 (± 0.931)	0.867	3 (18.8%)	8 (50%)	3 (18.8%)	2 (12.5%)		
I would need the support of a technical person to be able to use this simulator	2.73 (±1.438)	2.067	3 (18.8%)	5 (31.3%)	2 (12.5%)	4 (25%)		1 (6.3%)
Training Potential								
Most students would learn to use this simulator very quickly	3.88 (±1.03)	1.05		3 (18.8%)		9 (56.3%)	4 (25%)	
I believe that I would be a better dentist now if I had received Simodont® training during my undergraduate training	3.44 (±1.504)	2.263	2 (12.5%)	1 (6.3%)	7 (43.8%)	2 (12.5%)	2 (12.5%)	2 (12.5%)
I felt very confident using Simodont® simulator.	3.38 (±1.15)	1.32	1 (6.3%)	2 (12.5%)	5 (31.3%)	7 (43.8%)		1 (6.3%)
Would be a useful educational tool in preclinical dental training	4.5 (±.816)	0.667			2 (12.5%)	5 (31.3%)	8 (50%)	1 (6.3%)
Would be a useful tool in early dental skill training	4.38 (± 0.5)	0.25				10 (62.5%)	6 (37.5%)	
Would be a useful tool in advanced dental skill training	3.44 (±1.365)	1.863	2 (12.5%)	2 (12.5%)	2 (12.5%)	8 (50%)	1 (6.3%)	1 (6.3%)
I believe that the Simodont® can replace the traditional dental simulators	2.44 (±1.263)	1.596	2 (12.5%)	10 (62.5%)	1 (6.3%)	2 (12.5)		1 (6.3%)
I believe that the Simodont® can supplement traditional dental training	4 (±1.095)	1.2	1 (6.3%)	1 (6.3%)		9 (56.3%)	5 (31.3%)	
I recommend the use of Simodont® to new dental trainees	4.5 (± 0.632)	0.40			1 (6.3%)	6 (37.5%)	9 (56.3%)	
Indirect vision exercise								
The indirect vision exercise in the Simodont® is helpful for practicing mirror vision skills	3.94 (±1.063)	1.129		3 (18.8%)		8 (50%)	5 (31.3%)	
The indirect vision exercise experience in the Simodont® approximates the phantom head exercise experience	3.06 (±1.289)	1.663	1 (6.3%)	6 (37.5%)	2 (12.5%)	6 (37.5%)		1 (6.3%)

3.3.4 Response differences based on Specialism

There were no statistically significant differences among participants (grouped by dental specialism) in any of the responses to sections B and C of the questionnaire as assessed by Kruskal-Wallis H test for each item (*p's* > 0.05). The combined overall ratings for the Simodont® realism, training potential and difficulty of use by participants' specialism are presented in (Figure 3-7).

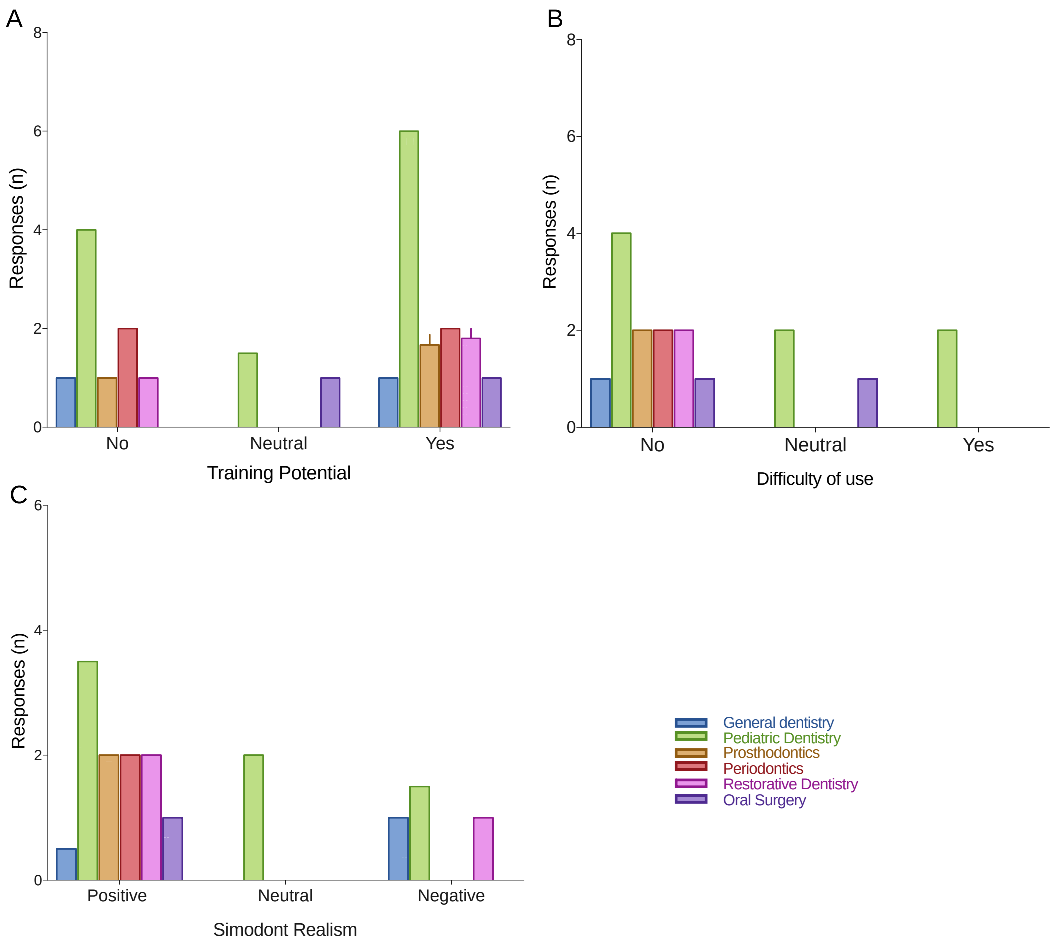


Figure 3-7 Combined overall ratings for the Simodont's® [A] training potential; [B] difficulty of use and [C] realism by participants' specialism.

3.3.5 Free text comments/feedback

Free text comments were provided by 8 (50%) participants only, and the contents were analysed and coded into two main themes (technical and realism) and presented in (Table 3.3-c). Half of the feedback (four comments) was about technical issues in the simulator particularly the lack of finger support during task performance, the difficulty in handpiece and mirror movements. The other three comments were about the simulator realism in general, and specifically (addition of water to handpiece).

Table 3.3-c Free text comments by some participants (n=8), with content coding and main themes.

Text Comment	Code	Theme
"Adding water virtually to Simodont® would make it better simulator for oral environment especially during cavity preparation."	Adding water to handpiece	Realism
"Hand piece felt heavy and stiff hard to move around"	Handpiece maneuverability	Technical
"Thanks for a very interesting experience"	Positive	Experience
"The main problem I encountered and wish to point out was the lack of proper finger support when using Simodont® specially for the indirect vision (i.e. no jaw or other teeth or other facial structure to help support hand to keep handpeice stable) which forms a big difference in training skills."	Finger support	Technical
"I found phantom head simulator more realistic than Simodont® but training could be improved by adding Simodont®. I have never used Simodont® before so it could be a good tool but with regular use."	Supplement Phantom head	Realism
"It was a great experience but I didn't think it simulated real dental work. Thank you for giving me a chance to try it :)"	Didn't simulate real dental work	Realism
"It was initially difficult to get used to for me. I didn't like the movements of the mirror but if I used it more I would be able to work it out"	Mirror movements/control	Technical
"It would be great if the simulator was provided with a part to help fingers support when using the hand piece (like we do on adjacent teeth in real patient). This will give better control on light touches with the handpeice specially for indirect vision (I found it difficult to control the drilling without supporting my other fingers)"	Finger support	Technical

3.4 Discussion

Simodont® haptic dental simulator was well accepted by the postgraduate dentists who participated in this study. They rated the simulator as realistic (mean range 2 - 2.94) particularly the visual, auditory and 3D realism. This is in agreement with previous studies on Simodont® realism (Bakr et al. 2013; Vervoorn & Wesselink 2009). Yet in the free text comment, some participants elaborated on the realism of the simulator and point out some missing elements (e.g. water cooling in the handpiece, finger rest). Similarly, general dentists in a previous study were critical about the realism of Simodont® (Vervoorn & Wesselink 2009), potentially because they might be comparing it with real clinical work and not with training on conventional non-computerized simulator.

Other realism issues in our results include the force feedback, hardness and handpiece manoeuvrability, which mainly related to haptic realism (functional fidelity), as one participant commented about the stiffness of the handpiece and cutting efficiency, and the other commented about the control over mirror movement. This is also in agreement with participants' experience in one study (Bakr et al. 2013) who commented about the weight of the handpiece and its cutting efficiency, and in another study with general dentists who were specifically not satisfied with force feedback of the simulator (Vervoorn & Wesselink 2009).

Generally the participants did not find difficulty in using Simodont®, but some of them believe that technical support might be needed.

Most participants found the indirect vision exercise on Simodont® to be helpful, however, there was some uncertainty regarding its similarity to the indirect view exercise in phantom head. This was totally expected, as the participants were dentists with clinical experience and the level of simulation of mirror vision is compared to their current real experience and their undergraduate training on typodonts. However, for first year dental students this particular exercise is potentially very helpful (as pointed out by some participants) in introducing the concept of mirror vision skills in a game-like feature, which then can be enhanced and built upon through more realistic physical training on the phantom head. Moreover, two participants pointed out the lack of finger support, a technical issue that adversely affect the indirect vision performance, and has been also previously raised in another study (Bakr et al. 2013). The finger rest is crucial to achieve hand steadiness that facilitates controlled finger movements necessary for the fine dental manoeuvres.

With regard to the training potential of the simulator, almost all participants agreed that Simodont® is a valuable training tool for undergraduate dentistry particularly in early skill training and would recommend it to new dental trainees, however, they believe that it can only supplement the conventional phantom head simulator but not totally replace it. Additional confirmation from the free text feedback revealed that although, they did appreciate its uniqueness and value, it is clear that they see the phantom head simulator as more realistic and better able to simulate dental work. This is in agreement with all previous studies on face validation of Simodont® (Bakr et al. 2013; Farah-Franco et al. 2016; Vervoorn & Wesselink 2009; Bakr et al. 2014; Bakr et al. 2015). This is not surprising, as the features of both simulators and the type of simulated procedures that can be performed are different. This should not be discouraging, but rather a catalyst for improving the simulator current features to meet the need of the end user (dental students and educators), which calls for an interdisciplinary approach (involving dentists, dental educators, students, psychologists, and engineers) during the design and upgrade stages of the simulator. It is also important for dental educators to structure the preclinical simulation experience with a sound pedagogical approach that utilizes the simulation methodology based on the learning objectives and specific learning contexts, rather than adapting the learning process to the available simulator features.

3.5 Conclusion

Simodont® was well accepted by most of the participating postgraduate students, who believe that it is a valuable training tool to supplement, but not to replace the existing phantom head simulator. Some participants were critical about the force feedback, hardness and handpiece manoeuvrability, which mainly related to haptic realism (functional fidelity) of the simulator. Generally the participants did not find difficulty in using Simodont®, but some of them believe that technical support might be needed and raised some technical issues (such as the lack of finger support) that need to be addressed. No differences were found among participants based on their dental specialty in any aspect of the simulator evaluation responses. Interdisciplinary approach to the design and upgrade of this simulator and other VR simulators is recommended to optimize its utility.

Chapter 4 : The predictive validity of Simodont® virtual reality haptic dental simulator

Among the primary research interests in the utility of VR simulators is whether they can be of predictive value for future preclinical and clinical dental performance. Prediction of future dental performance (both academic and clinical) has been always a fundamental concern for dental educators. Early identification of potential students who are more likely to thrive in dental school and beyond has both pedagogical, administrative and economic implications (Ranney et al. 2005; Urbankova et al. 2013). While it allows for early intervention, focused instruction and support for the weak/challenged students, it also facilitate a better selection process at the outset with objective criteria particularly with the growing number of dental schools applicants.

The distinction between cognitive abilities (academic performance) and perceptual abilities (psychomotor skills) as predictors of dental performance has been advocated (Smithers et al. 2004), as each has its own characteristics , skill sets and conditions that influence their predictability.

A wide range of predictors of academic performance has been investigated in the dental literature, for example, GPA (grade point average) (Sandow et al. 2002; Curtis et al. 2007), DAT (dental aptitude test) (Wood & Boyd 1982; Kramer 1986; Carroll & Schuster 2015), UKCAT (United Kingdom clinical aptitude test) (Lala et al. 2013), MMI (multiple mini interviews) (Foley & Hijazi 2013; McAndrew et al. 2016), and personality profiles (Poole et al. 2007; Chamberlain et al. 2005; Jones et al. 1997).

While the prediction of early academic performance in dental school has been identified to some extent with the use of prior academic grades and various admission tests, the prediction of psychomotor skill/manual dexterity practical performance of dental students in preclinical and clinical settings is less evident and not clearly defined (Urbankova & Engebretson 2011b). A wide range of predictors of psychomotor skills have been investigated (Table 3.5-a) including chalk carving tests (Gansky et al. 2004; Ballard et al. 2015; Peterson 1974), waxing tests (Walcott et al. 1986) , wire-bending tests (Kao et al. 1990; Kothe et al. 2014), tweezers dexterity test (Lundergan et al. 2007), spatial ability tests (Heintze et al. 2004), Crawford Small Parts Dexterity test (Boyle & Santelli 1986; Spratley 1992) and other standard psychometric tests (Suksudaj et al. 2012; Causby et al. 2014) as well as other predictors (Luck et al. 2000; Boushell et al. 2011; Gray & Deem 2002; Zawawi et al. 2015).

The majority of the investigated manual dexterity tests revealed a limited predictive value, and it has been suggested to utilise them as screening tools rather than predictors of performance (Ranney et al. 2005). The limited predictive value of even well established psychomotor tests has been attributed to incomplete understanding of the specific psychometric properties of the tests and more important, to the limited relevance of the tests to the specific dental tasks being predicted (i.e. reduced generalizability) (Causby et al. 2014).

Table 3.5-a Summery of key studies (in chronological order) on the prediction of practical dental performance.

Author (year)	Sample (N)	Predictor	Outcome	Main findings
Boyle and Santelli (Boyle & Santelli 1986)	71	The Crawford Small Parts Dexterity Test	Mean performance in four preclinical laboratory courses	The test may improve selection accuracy when used with other admission criteria.
Walcott et al., 1986 (Walcott et al. 1986)	131	Two waxing test	Eight preclinical performance measures	The waxing tests are better predictors than the perceptual portion of the DAT. May be useful in the early identification of weak students.
Kao et al., 1990 (Kao et al. 1990)	105	Wire-bending test	Grades from seven restorative preclinical courses	Wire-bending scores correlated significantly preclinical restorative courses and identified low performing students.
Spratley , 1992 (Spratley 1992)	45	Battery of 3 manual dexterity tests developed based on Crawford Small Part Dexterity Test.	Practical examination in dental technology	No correlation
Gansky et al., 2004 (Gansky et al. 2004)	244	Chalk carving (plaster block carving)	Preclinical restorative course performance	No correlation
Lundergan et al., 2007(Lundergan et al. 2007)	50	Two different types of tweezers dexterity tests (Johnson O'Connor Test #32022 and #18)	-First year Practical performance at 5 courses. -Cumulative GPA -Overall rank at time of graduation	The predictive power of tweezers dexterity tests for the seven educational outcomes measures was weak.
Boushell et al., 2011 (Boushell et al. 2011)	81	Learn-A-Prep II	Practical examinations in a preclinical restorative dentistry course.	The depth aspect of performance on the LAP II was predictive of practical performance only early in the course.
Suksudaj et al., 2012 (Suksudaj et al. 2012)	2 cohorts 2007(n=52) 2008(n=74)	Selected standard psychometric tests: Cognitive, perceptual speed and psychomotor ability tests	(MOD) cavity preparation exercises on plastic teeth	both innate psychomotor ability and motivation showed only weak associations with dental performance on cavity preparation exercises.
Kothe et al., 2014 (Kothe et al. 2014)	3 student cohorts 2008(n=23) 2009(n=69) 2010 (n=54)	Wire bending test (HAM-Man)	Practical performance in the first two laboratory courses	Significant correlations for all cohorts between HAM-Man and performance. Explained up to 20.5% of performance variance.
Ballard et al., 2015 (Ballard et al. 2015)	176	Chalk carving exercise	Grade in preclinical operative dentistry	Positive correlation between the chalk carving scores and the preclinical operative dentistry course grade.
Moravej-Salehi et al., 2016 (Moravej-Salehi et al. 2016)	92	-Handwriting Test -Drawing Test	Class I Amalgam cavity on Typodont	Significant association between drawing and cavity preparation skills; although not clinically considerable.

The use of preclinical dental simulator performance to predict clinical performance has been the focus of many studies, since the preclinical simulated restorative tasks are close in some aspects to the actual clinical cases. Nevertheless, the results of these studies varied widely.

The first group of studies investigated the phantom head simulator performance to predict later preclinical and/or clinical performance. An early preclinical performance of Class I cavity preparation for amalgam restoration on a typodont has a limited predictive value of students performance later in the preclinical course, suggesting that manual skills were improved during the practical training and the low performers early in the course improved considerably with training and scored high later (Polyzois et al. 2011). In another study, no correlation was found between the students preclinical performance on typodont (two full veneer crown preparations for a fixed partial denture case with provisional restorations), and subsequent clinical performance on live patients (full crown preparation with provisional restoration fabrication) (Curtis et al. 2007). Similarly, student full PFM crown performance in the clinic did not correlate with preclinical typodont performance, with greater variability and lower scores in the clinical test (Nunez et al. 2012). On the other hand, a retrospective study of two cohorts found a significant association between the students' preclinical performance (in operative dentistry and fixed prosthodontics courses) and their clinical performance; the researchers highlights the need for further studies to identify the specific factors that affect preclinical and clinical performance and contribute to this association (Velayo et al. 2014). The difficulty in finding a definite predictive relationship between the multidimensional clinical performance and the fairly standardised preclinical typodont tests performance can possibly be attributed to several factors such as the contextual differences between the two settings (dental clinic and preclinical laboratory) and patient case variability.

The second group of studies investigated the performance on virtual reality dental simulators as predictor of early and later preclinical performance. Computerized AR dental simulator pre-test performance correlated significantly with the students' early preclinical course performance but not with their later performance where more complex dental procedures were involved. However, the study did not conclude the predictive value of the computerized simulator as this was limited by the relatively small sample size and the technical sensitivity of the device according to the authors (Gray et al. 2003) . In another study, AR simulator (DentSim) pre-test correlated positively and predicted the students' performance in preclinical manikin course (Imber et al. 2003). Similarly, DentSim pre-test performance predict the students' performance in early (but not later) preclinical operative dentistry course, suggesting its diagnostic utility in early identification of students challenged by complex manual dexterity tasks (Urbankova & Engebretson 2011a).

The ability of VR haptic dental simulators to predict future preclinical dental performance was also investigated. In a study using IDEA® (Individual Dental Education Assistant simulator), three haptic dental tasks were used to identify the best predictors of preclinical operative dentistry performance, and a strong association was found between the more complex haptic exercise and preclinical operative dentistry performance (Urbankova & Engebretson 2011b). In a follow-up study, the authors tested dental students on a complex haptic exercise in eight consecutive trials measuring both accuracy and time to completion and found it to correlate significantly ($p<0.05$) with early preclinical operative course performance (Urbankova et al. 2013). In a recent study, using Simodont® haptic dental simulator, the students performance of basic haptic exercise (achievement of 60% and 75% target levels) was statistically significantly correlated with their performance at the preclinical operative dentistry course with high sensitivity values (i.e. students who passed the haptic test at 60% and 70% were significantly more likely to pass the preclinical test) (Polster et al. 2015).

Thus, convergent evidence from previous studies on the predictive value of dental VR simulators indicate they could predict only early preclinical performance but not later performance, where the correlation with the basic skills and abilities would have been possibly diluted by learning/practice effect during the preclinical course. Furthermore, there are no reported studies, so far, on the prediction of clinical dental performance from haptic dental simulator performance. The possible association between early preclinical haptic simulator performance and clinical performance is not straightforward and subject to many confounding variables that potentially affect the student performance in both settings. However, investigating such issue would provide valuable insights into the ability of such simulator to selectively identify the core abilities required for successful performance even later in the actual clinical environment where the students arrive with a cumulative reservoir of skills learned throughout their intensive preclinical training.

Therefore, this retrospective cohort study set out to investigate the potential of VR haptic dental simulator Simodont® to predict preclinical and clinical dental performance among a single undergraduate student cohort in one dental school. We hypothesized that early preclinical performance on Simodont®

haptic simulator by undergraduate dental students is associated with their preclinical and clinical performance.

4.1 Aim and objectives

The aim of the current study is to examine the predictive value of VR haptic dental simulator in undergraduate dental performance.

The objectives are:

1) To explore the relationship between students' preclinical performance on Simodont® (Year 2 of dental school) and their subsequent performance in two preclinical and one clinical tests as follow:
    - a- Preclinical phantom head simulator tests:
        - I. Spotter test (Year 2)
        - II. Typodont full crown preparation test (Year 3).
    - b- Clinical test at fourth year:
        - Full crown preparation test on live patients.
2) To explore the relation between the students' preclinical performance in phantom laboratory tests (at Years 2 and 3) and their subsequent clinical performance (at Year 4)

4.2 Methods

4.2.1 Participants

The 2012 cohort of undergraduate dental students (N=72, 46 female, 26 male) at the School of Dentistry, University of Leeds, were selected for this retrospective study. Ethical approval to access the students' data was obtained from DREC (Dental Research Ethics Committee) at the School of Dentistry, University of Leeds (DREC ref: 230915/LA/178).

4.2.2 Performance assessment results

A total of four practical tests results (three preclinical, and one clinical) were obtained for each student (Figure 4-1) from the student education office and from the module leaders. Confidentiality was maintained by assignment of code numbers replacing students name.

4.2.2.1 Preclinical performance results:

1. Year2- Virtual Reality Haptic dental simulator (Simodont®):

   The average results of students practice trials on manual dexterity exercises available in the Simodont® courseware (ACTA, the Academic Centre for Dentistry, Amsterdam, the Netherlands).

   ⇒ Due to the large number of trials performed by each student for different exercises and due to differences in number of trials per student, we standardize the selection criteria in the current study as follow: the number of trials included per student is 33 and the minimum task completion level is 60%. *N.B:* In an attempt to include the full cohort, I searched for all the successful trials by each student, then found that the minimum number of trials was 33 (i.e. the maximum number performed by one of the student), based on that I decide to use that number for all the students in the cohort to minimise variability. The results for each trial done by each student were downloaded from the Simodont® server, filtered, arranged in Excel sheets, calculated and exported to SPSS for analysis.

2. Phantom head simulator:

a- *Year2-Spotter test*: performed in the phantom head using typodont with mounted plastic teeth. In this laboratory test, the students were asked to spot the wrong/defective part of a preparation or restoration. Afterwards, the dental instructors assign a final mark out of 100 to each student based on his/her performance.

b- *Year3-Crown test*: Full crown preparation on typodont with mounted plastic teeth in the phantom head simulator, 40% of the grade of this test is assigned to the student critical self-evaluation (the ability to critically evaluate his/her own work e.g. identify preparation errors).

4.2.2.2 Clinical Performance results:

- Year 4 -Full PFM clinical crown preparation test on real patients.

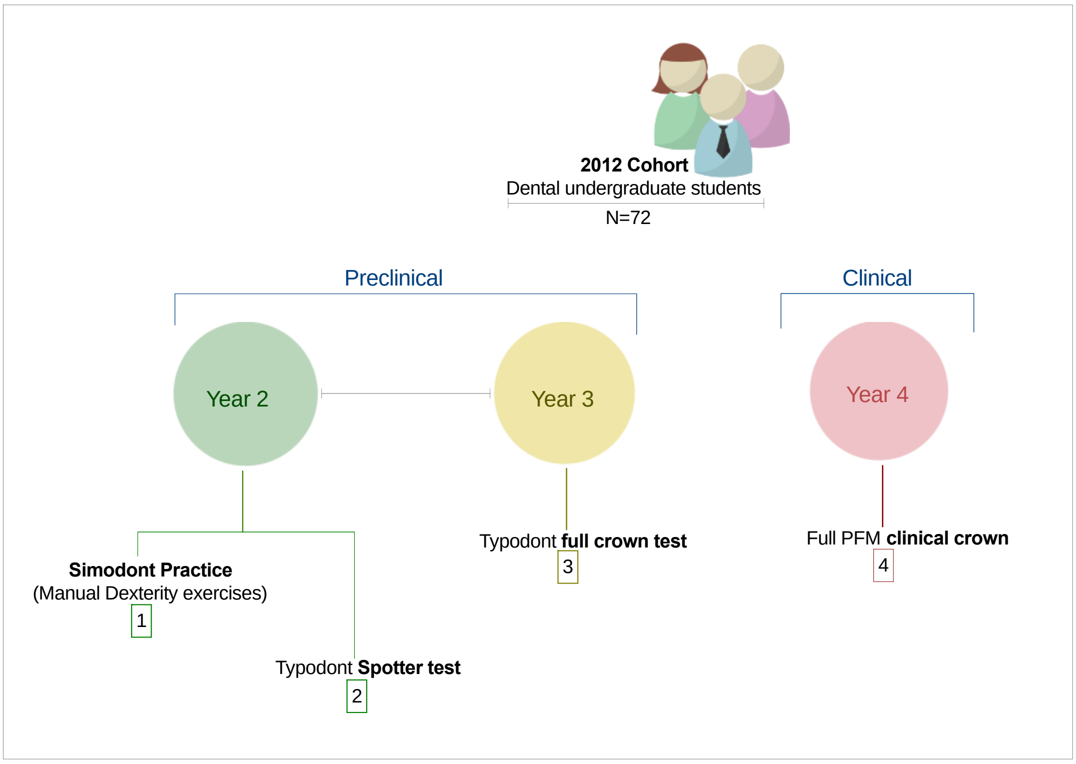


Figure 4-1 Flowchart of the 4 performance assessments investigated retrospectively in the current study.

4.2.3 Data collection and statistical analysis

This study used a quantitative methodology. Preliminary analyses showed that all continuous variables (test results) were normally distributed, as assessed by Shapiro-Wilk's test (p > .05), and there were no outliers.

Pearson's product-moment correlation was run to assess if there is any association between students' performance at any of the four tests separately for each pair of tests. The strength of association was interpreted based on Cohen's (1988) guidelines : small correlation (0.1< r <0.3), moderate correlation (0.3< r <0.5), and strong correlation (r >0.5).

Multiple regression analysis was run to explore the relation between students' clinical and preclinical performance, with clinical crown test performance as the dependent variable and preclinical tests (VR Simodont®, Spotter test, and preclinical crown test) as the predictors (independent variables).

The students numerical test scores in the current study were further categorized into dichotomous (low/high performers) distinction based on each test overall results (appendix A.2.1), and the proportion of high and low performing students at each test were calculated. Fischer exact test was used to compare proportions of high performing students at the clinical crown test with high performing students at each preclinical test. Odds ratio and 95% confidence intervals were calculated for high performance at the clinical crown test (dependent variable) according to high performance at all three preclinical tests (independent variable).

Sensitivity and specificity of each preclinical test to predict clinical crown test performance were also calculated. The operational definitions of sensitivity, specificity and predictive values in the context of fine motor skill testing as described in the current study, are presented in Table 4.2-a.

The statistical significance threshold was set to $p < .05$. All statistical analyses were performed using IBM SPSS® Statistics for Windows (Version 22, Armonk, NY: IBM Corp., 2013).

Table 4.2-a The operational definitions of sensitivity, specificity and predictive values in the context of fine motor skill testing as described in the current study.

Test feature	Operational definition
Sensitivity	Indicates how accurately does the test identify high performing students who would be also high performers in a clinical test (i.e. the true positives).
Specificity	Indicates how accurately does this test identify low performing students who would also be low performers in a clinical test (i.e. the true negatives).
Predictive value	The ratio of correctly identified high performing students to all high performers (i.e. true positives to all positives)(Domino & Domino 2006)
Positive predictive value (PPV)	The proportion of positive test (high performers) that are true positives (correctly identified high performing students)
Negative predictive value (NPV)	The proportion of negative test (low performers) that are true negatives (correctly identified low performing students).

4.3 Results

Descriptive statistical measures of the mean, standard error of the mean, and coefficient of variation were determined for describing the characteristics of all the practical tests and graphically plotted at (Figure 4-2**).**

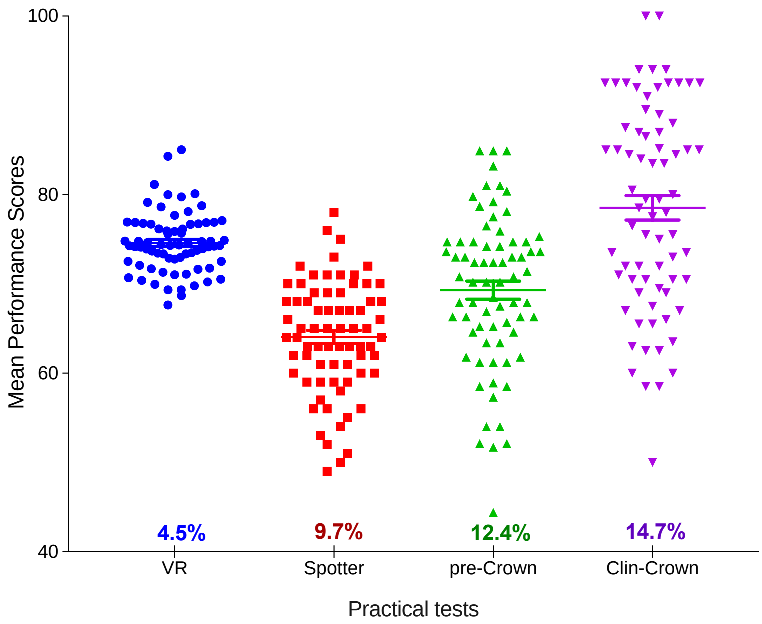


Figure 4-2 Dot plot of the students' performance scores in the four practical tests (N=72), showing the Mean and standard error of the mean (SEM). The Coefficient of variation (CV) of each test is shown as percentages.

4.3.1 Correlation Analysis

4.3.1.1 Simodont® VR test and Phantom head tests:

a- Spotter test performance:

No statistically significant correlation was found between students' performance at Simodont® and the typodont spotter test, $r\ (70) = 0.076$, $p = 0.526$.

b- Preclinical crown test performance:

Similarly, no statistically significant correlation was found between students' performance at Simodont® and preclinical crown test on typodont, $r\ (70) = -0.006$, $p = 0.961$.

4.3.1.2 Simodont® VR test and Clinical crown test:

Pearson's correlation test revealed a moderate positive correlation between students' performance at Simodont® and the clinical crown test results at year 4 of dental school, and it was statistically significant, *r* (70) = 0.377, *p*= 0.001.

4.3.1.3 Preclinical Phantom head tests and Clinical crown test:

a- Clinical crown test results and Spotter test results:

Students' performance at the clinical crown test and typodont spotter test were statistically significantly correlated *r* (70) = 0.237, *p*= 0.045.

b- Clinical crown test results and Preclinical crown test results:

Students' performance at the clinical crown test and the preclinical crown test on typodont were not significantly correlated *r* (70) = 0.221, *p*= 0.062.

4.3.1.4 Preclinical Phantom head tests:

Students' performance at both phantom head tests (spotter and preclinical crown) were not significantly correlated *r* (70) = 0.139, *p*= 0.246.

Summary of the correlations between all four practical tests is shown in Figure 4-3.

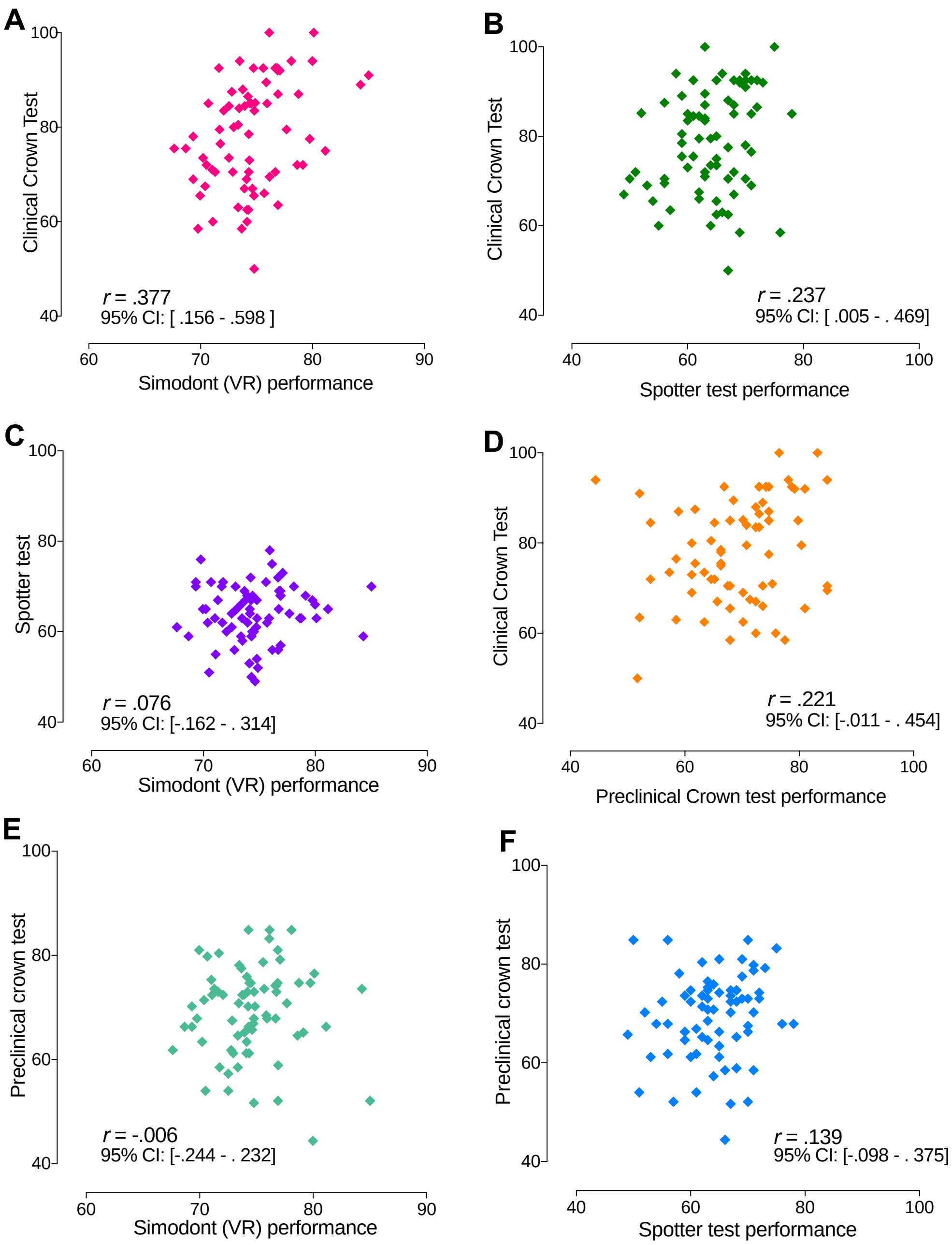


Figure 4-3 Scatter plots for Inter-tests performance correlations with 95% CI. [A] Simodont and clinical crown tests, [B] Spotter and clinical crown tests, [C] Simodont and spotter tests, [D] Preclinical crown and clinical crown tests, [E] Simodont and preclinical crown tests, and [E] Spotter and preclinical crown tests.

4.3.2 Regression Analysis

To further explore the relation between students' clinical and preclinical performance, first , individual linear regression analyses were run for each preclinical test alone as predictor for the clinical crown test performance (Figure 4-4). Subsequently, multiple regression analysis [method: stepwise] was conducted with clinical crown test performance as the dependent variable and preclinical tests (VR Simodont®, spotter test, and preclinical crown test) as the predictors (independent) variables.

The multiple regression assumptions were all examined as follow:

- There was independence of residuals, as assessed by a Durbin-Watson statistic of 1.597.
- There was homoscedasticity, as assessed by visual inspection of a plot of studentized residuals versus unstandardized predicted values.
- There was no evidence of multicollinearity, as assessed by tolerance values greater than 0.1. Levels of *F* to enter and *F* to remove were set to correspond to *p* levels of .05 and .10, respectively, to adjust for familywise alpha error[9] rates associated with multiple significance tests.

  a. *VR Simodont alone as predictor of clinical crown performance:*

  A significant regression equation was found F (1,70)= 11.58, p=.001, with an R^2 of .142. This indicates that Simodont performance explained (predicted) 14.2% of the clinical crown test performance with adjusted R^2 of 13%, a medium size effect according to Cohen (1988).

  b. *Spotter test alone as* predictor of clinical crown performance:

[9] Also known as alpha inflation (type 1 error-incorrect rejection of the null hypothesis). It is the probability of coming to at least one false conclusion in a series of hypothesis testing.

F (1,70)= 4.167, p=.045, with an R^2 of .056. This indicates that spotter test performance explained (predicted) only 5.6% of the clinical crown test performance with adjusted R^2 of 4.3%.

c. *Preclinical crown test as predictor* of clinical crown performance: *F* (1,70)= 3.602, p=.062, with an R^2 of .049. This indicates that preclinical crown test performance statistically explained only 4.9% of the clinical crown test performance with adjusted R^2 of 3.5%.

d. Multiple regression model: The best fitting model for predicting clinical crown test performance is a linear combination of VR Simodont® performance at year 2 and preclinical crown test performance at year 3, R =. 438, R^2 =. 192, F (2,69) = 8.192, p=. 001.

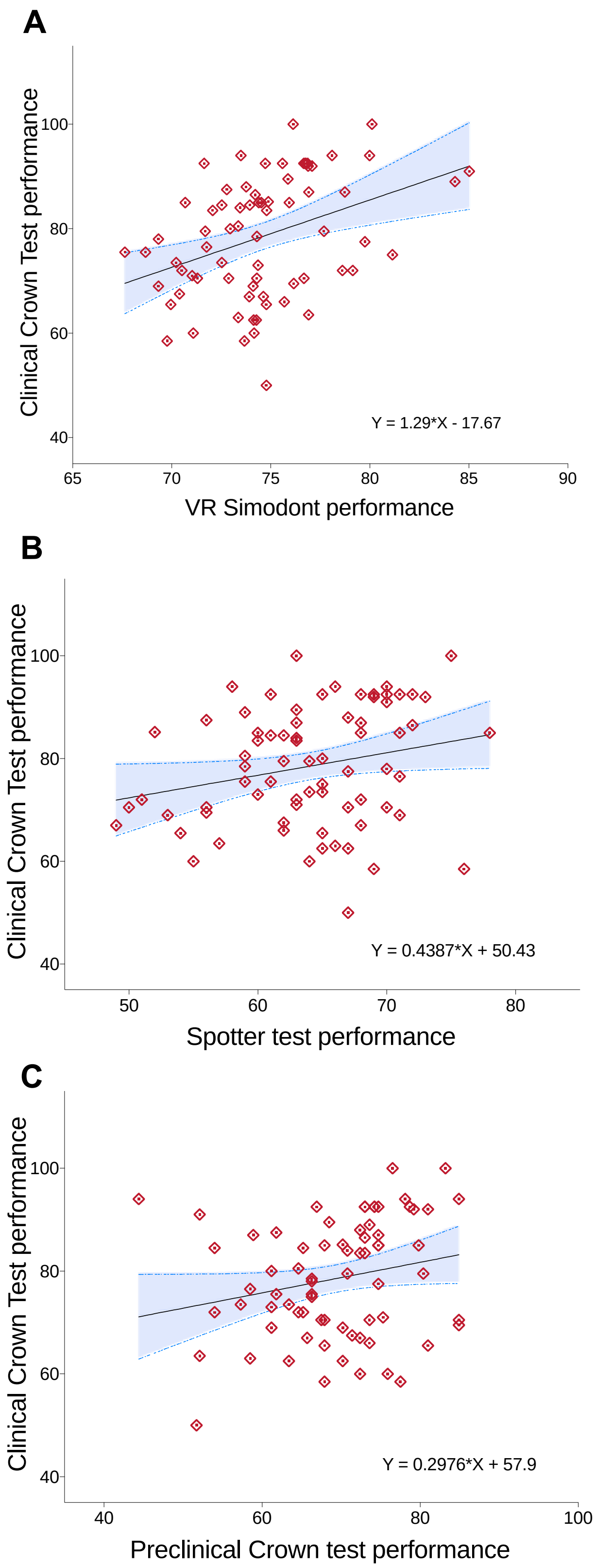


Figure 4-4 Regression analyses with fitted regression lines and regression equations for the prediction of clinical crown test performance with [A] VR Simodont® performance as predictor, [B] Spotter test performance as predictor, and [C] Preclinical crown test performance as predictor. The dotted blue lines represent 95% CI.

4.3.3 Odds ratio, sensitivity, and specificity

Students who were high performers at Simodont® assessment were 10.241 times more likely (95% CI [1.223, 85.781]) to be high performers at clinical crown test as well (2-sided Fischer exact p=. 015). Simodont® predicted clinical crown test performance with 97.1% Sensitivity and 23.7% specificity.

Students who were high performers at preclinical typodont spotter test were only 1.780 times more likely (95% CI [.607, 5.224]) to be high performers at clinical crown test as well (2-sided Fischer exact p=. 422) and that was not statistically significant. Therefore, spotter test is a weak predictor of clinical crown test performance with 79.4% Sensitivity and 31.6% specificity.

Students who were high performers at preclinical crown test were only 2.875 times more likely (95% CI [1.095, 7.545]) to be high performers at clinical crown test as well (2-sided Fischer exact p=. 036). Although a weaker predictor than Simodont®, preclinical crown test is better than spotter test at predicting clinical crown test performance with 67.6% Sensitivity and 57.9% specificity. Sensitivity and specificity values for all three preclinical tests are shown in Figure 4-5.

The Receiver Operating Characteristic (ROC) curve analysis was done for the three predictors, Simodont® , spotter and the preclinical crown test (**Figure 4-6**). The area under the curve (AUC) for Simodont® was better than that of both typodont tests, while spotter and preclinical crown tests have comparable AUC values (Table 4.3-a).

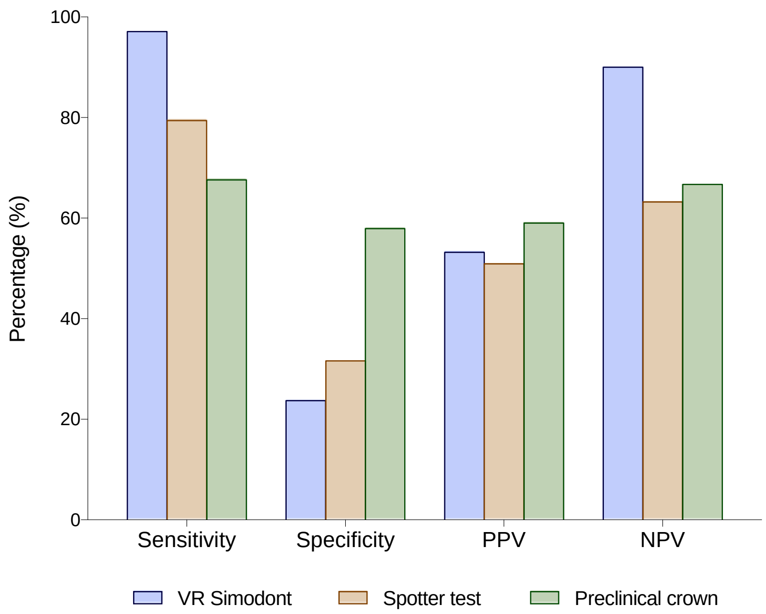


Figure 4-5 Sensitivity, specificity, positive predictive value (PPV) and negative predictive value (NPV) of the 3 preclinical tests for prediction of clinical crown test performance.

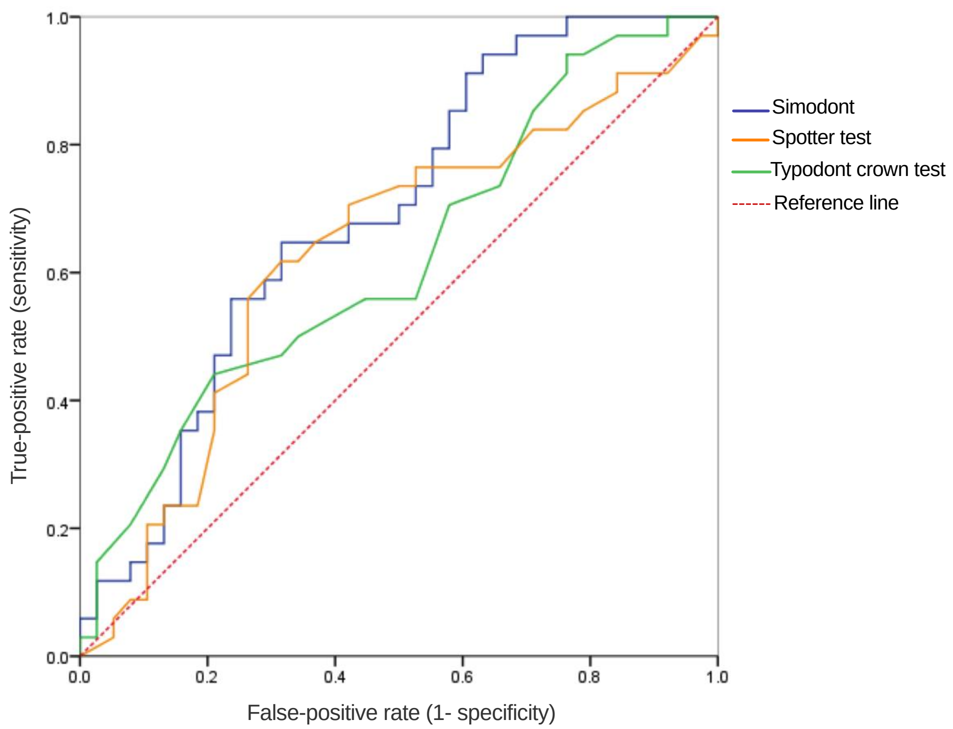


Figure 4-6 The Receiver Operating Characteristic (ROC) curve analysis for the predictors, Simodont® , spotter test and the preclinical crown test.

Table 4.3-a The area under the curve values, AUC_{ROC} (with 95% CI) for the three predictors.

	AUC *(Area Under the Curve)*	95% Confidence Interval	
		Lower bound	Upper bound
VR Simodont	.689	.567	.811
Spotter	.622	.493	.752
Preclinical Crown	.628	.496	.761

4.4 Discussion

The results from the current study revealed a medium positive correlation between VR haptic simulator performance and subsequent clinical crown test performance among a group of undergraduate dental students. Moreover, this correlation exhibited a statistically significant predictive value with implications for expanding the utility of haptic simulator further in preclinical undergraduate dental education.

The Simodont® assessment in the present study was standardized to include an average of multiple trials with no less than 60% target level for each student, on basic manual dexterity exercises available in the Simodont® courseware. These trials were spread over multiple sessions as a formative assessment and performed early on in the second year practical training before phantom head simulator training. The possible implication of these specific training conditions on the results obtained may be explained through several points related to both the learner and the learning context. Although the assessment was for basic abstract manual dexterity tasks, they were correlated with actual clinical performance - two essentially different performance settings. This may be attributed to the possibility that the simulator specifically identified common basic abilities required for dental performance such as the precision in holding and manipulating the handpiece, the ability for controlled cutting/drilling in depth, and other factors related to the basic fine motor abilities of the student. Besides, the formative nature of this assessment implied that students practiced in relaxed/non stressful atmosphere on their own time, possibly motivated by the aspiration to practice dentistry (virtually) early on in the dental school, to improve their manual skills, and/or to gain the instructor and peer recognition for achieving the best training results at the end of the module. This has been facilitated by the capabilities offered by the haptic simulator particularly the unlimited practice reiteration without the need for extra resources, and the real-time objective evaluation on each trial provided automatically by Simodont®. This draws our attention to the unique research opportunity provided by Simodont® to study the effect of deliberate practice (Ericsson 2004) on fine motor skill development and refinement, an important, yet relatively unexplored, concept in dental education research.

Our data showed no correlation between Simodont® assessment and any of the phantom lab typodont preclinical tests (i.e. 2nd year spotter test, and 3rd year typodont crown test). These particular findings are different from what has been reported previously by Polster et al. (2015) and by Urbankova et al. (Urbankova et al. 2013; Urbankova & Engebretson 2011b), where a positive association were found between students performance on haptic simulators assessment and typodont exams. One of the primary differences between (Urbankova et al. 2013; Urbankova & Engebretson 2011b) studies and ours, is that the association was between single session haptic exercise and 3 preclinical operative dentistry exams (mainly simple and compound Class II as well as Class III) and the association was with early preclinical performance but not later. While in our study the haptic assessment was 33 exercises spread over multiple sessions (at year 2) and the typodont exam was one full crown preparation (at year 3).

On the other hand, performance in both phantom lab typodont tests was correlated, albeit weakly, with the clinical crown test performance in the present study. However, the predictive value was less than that obtained from Simodont®. This is in agreement with Velayo et al. (2014) who reported that preclinical training on typodont is associated with the clinical performance with weak predictive value. Similarly, An OSCE-based knowledge exam (where the students were asked to identify critical errors in preparation and casting of FPD) was found to be weakly correlated with the clinical performance of full crown competency exam (Curtis et al. 2007). In contrast, reports from other studies showed no correlation between preclinical training on typodont and subsequent clinical performance (Curtis et al. 2007; Nunez et al. 2012). It is important to highlight that the interpretation and comparison with other studies is limited by the wide disparity in methodological approaches to typodont exams and grading criteria, in addition to the inherent variations expected in clinical settings due to differences among patients' conditions.

The coefficients of variation of all four tests in the current study were calculated to explore the relative variability in scores at different assessment settings. The highest score variability was reported for the clinical crown test, and the least variable scores were for Simodont® assessment. This gradual difference in performance scores is anticipated, since the clinical setting variability implies that each clinical case/patient is different despite the specific criteria used to standardize the exam (e.g. mandibular or maxillary tooth, the presence of adjacent tooth, normal occlusion, etc.). Furthermore, the clinical experience is multifaceted affected by several factors that are difficult to standardize such as the dental characteristics of the patient (e.g. limited mouth opening, effectiveness of local anaesthesia), the patient attitude and behaviour, and the student stress/ anxiety level. On the other hand, the other tests are in preclinical simulated settings that are fairly consistent using identical plastic and virtual teeth.

In the current study, the typodont crown test at year 3 is, theoretically, the closest of all other preclinical tests to the actual clinical crown test, basically performing the same procedure in simulated (phantom typodont) and later in actual clinical (live patient) setting. This was reflected in the higher specificity values for the typodont crown test (57.9%) compared to the other preclinical tests (i.e. out of the 38 low performing students at the clinical crown test, 22 were also low performers at the typodont crown test). Moreover, typodont crown test in the current study was not only evaluating the fine motor skills of the students, but also evaluating the student self-critical ability, a part that contributes significantly (40%) to the final grade. The ability to accurately and realistically evaluate their own work imply that the students have clear understanding of the success criteria for that specific task, and are able to identify unsuccessful or less than optimal performance attempts. This important ability has been shown to affect the practical performance of undergraduate dental students significantly in preclinical dentistry, as high performing students reported to be more critical about their performance compared to low performing student (Cho et al. 2010) and improvement in their self-evaluation skill resulted in performance improvement (Curtis et al. 2008).

The spotter test at year 2 differs from the other two preclinical tests in the fact that it particularly tests the cognitive ability of the students to identify critical preparation and restoration errors rather than their fine motor skill per se. However, we found that it is more sensitive test (79.4%) than typodont exam (67.6%) in predicting clinical crown performance (i.e. out of 34 high performing students at the clinical crown test, 27 were also high performers at the spotter test).

Simodont® performance alone explained 14.2% of the variation in the clinical crown test with high sensitivity (97.1%) (i.e. out of 34 high performing students at the clinical crown test, 33 were also high performers at Simodont® assessment). The addition of typodont crown test contributes an additional 5% (p=. 043) to the explanatory power of the regression model. The spotter test results did not contribute significantly to the model and was excluded as a predictor in the stepwise regression analysis. The full model of Simodont® and typodont test raised the predictive value to 19.2%; this leaves 80.8% of the variation in clinical crown test performance to be explained by other variables (e.g. patient characteristics, student stress level, clinical environment) .

The differences among various tests and their predictive values may be explained in terms of incremental validity (Cohen & Swerdlik 1999), as each type of assessment (predictor) is included if it contributes specific aspects that can not be offered by other tests, collectively attaining predictive value that account for the inherently multidimensional learning experience, emphasizing the fact that there is no single ideal predictor for clinical dental performance yet, as each type of assessment is capturing a specific dimension of the clinical performance.

As mentioned earlier, there was a wide variation in Simodont® practice frequency among students in this cohort, while some of them had performed more than 80 trials, others did as low as 35 trials in total. This is not surprising, because there was no specific module requirement as to the amount of practice on Simodont®, so the student approach was self-directed learning, therefore the number of practice attempts varied widely.

The significant explanatory power of the clinical performance variations by Simodont® has important implications for its integration into the undergraduate dental curriculum, and the identification of its unique pedagogical potential. First, the early use of the simulator by dental students (at Year 2) is supported by the present findings, and we further suggest that there should be a minimum requirement for practice on the Simodont® (specifically manual dexterity exercises) before moving on to the next practical training stage in the curriculum. The rationale of such competency-based approach is that it will standardize the practice among students to an acceptable level, for example, x practice trials per module with minimum task goal of x%. The students are allowed to practice more if they wish, but not less than the minimum requirement, an approach that will cater for students' varied learning preferences and sensorimotor abilities. However, empirical evidence is needed to specifically determine the minimum acceptable practice requirement.

The second possible implication is the possibility of early identification of students with difficulties in performing basic manual dexterity tasks, and provides them with appropriate pedagogical support and structured practice sessions. For example, a student may struggle to achieve the success criteria of 60% at a task despite repeated performance attempts; the educator should be able to identify specifically what is the major contributor to this outcome (e.g. high depth errors draw the attention to the need for more control of handpiece pressure exerted by the student) and will direct the student practical efforts into more relevant direction that will improve the performance outcome. Despite the current promising results (especially the association between that successful practice attempts on Simodont® and good clinical crown test performance), we acknowledge the limitation of exploring a single cohort of undergraduate students in single institution. Larger validation studies are warranted on other dental cohorts and across other institutions. Moreover, future research should investigate how Simodont® training is related to other practical assessments across the preclinical and clinical undergraduate curriculum.

4.5 Conclusions

Significant correlation was found between VR haptic simulator performance and subsequent clinical crown test performance among a group of undergraduate dental students. Simodont® has a statistically significant predictive value which explained 14.2% of the variation in the clinical crown performance.

These findings have implications to expand the potential utility of haptic dental simulator Simodont® in the undergraduate dental curriculum.

Chapter 5 : Stereopsis and Dental performance

Despite the importance of depth perception in dental practice, the available literature about the how depth perception impacts dental performance is still limited (Arruda et al. 2008; Nick et al. 2009; Ricketts et al. 1995; Dimitrijevic et al. 2011). Additionally, the particular importance of stereopsis in dentistry has been debated and questioned (Syrimi & Ali 2015; Mon-Williams et al. 2015). Furthermore, the increased availability of VR dental simulators with stereoscopic displays demands careful evaluation of the possible factors that impacts their utility (e.g. human factors). Stereopsis is an important human factor issue that potentially influences the utilisation of VR simulators. These simulators provide a unique opportunity to address the fundamental issue of whether stereopsis has a functional role within dentistry. The Simodont® simulator presents an opportunity to examine this question as it can be engineered to provide a full binocular experience with or without stereoscopic viewing. This enables a robust investigation into the impact of removing stereoscopic information whilst keeping the other visual features of the display constant.

The next sections provide detailed overview about stereopsis, stereoscopic tests, prevalence and functional significance in Surgery and Dentistry.

5.1 Stereopsis

Stereopsis can be defined as the ability to perceive depth from binocular horizontal retinal disparity. It is a sensory process that represents the fundamental functional difference between monocular and binocular vision (Ogle 1959) . It is particularly advantageous in performance of fine motor tasks (especially in near distance) that need high levels of hand-eye coordination and comprehension of complex visual presentations (Fielder & Moseley 1996; Bloch et al. 2014). For goal-directed motor skills in close distance (within 2 meters), stereopsis is critical to prehension (the act of reaching and grasping an object to manipulate it to achieve specific goal), and functionally associated with it (Luursema et al. 2008).

Stereopsis is quantified as stereoscopic acuity or stereoacuity; which is defined as “the depth-discrimination threshold when binocular disparity is the only cue to depth” (Howard & Rogers 2002) . Stereoacuity is measured as the difference in angles subtended at the optical nodes of the eyes and expressed in minutes or seconds of arc (Gulick & Lawson 1976), and represent the minimum perceivable horizontal disparity (Lee & McIntyre 1996) that leads to three dimensional percept, and the smaller the angular measurement the better the stereoacuity. The stereoacuity unit of measurement [second of arc, arcsec,″] equals to 1/60 minute of arc and 1/3600 of a degree (Howard & Rogers 1995).

5.1.1 Tests

Stereoscopic tests have been utilized either as a screening tool (to indicate the presence or absence of stereopsis and other ocular disorders), or as a diagnostic tool to determine the stereoacuity threshold of the individual (level of depth discrimination) which can be improved with practice (Coutant & Westheimer 1993). While untrained human observer can discriminate relative depth disparity of 30 arc sec, experienced observers, with practice, can discriminate much fine disparities of as low as 4–8 arc sec (Wilcox & Allison 2009).

Classically, stereopsis has been tested using real objects (2-3 vertical rods) and the gold standard of such tests is the Howard-Dolman test (Howard 1919). Other types of stereopsis tests utilize stereoscopic devices (Davson 1962).

Stereopsis is subdivided into two main types: local and global stereopsis, both are dependent on binocular horizontal disparities. Local stereopsis accounts for monocular cues and is tested by contour stereogram tests; while global stereopsis is devoid of observable monocular cues and purely dependent on correlated retinal disparities and tested by random-dot stereogram tests. The monocularly visible contours in local stereopsis tests adjunct the oculomotor control and disparity fusion, and this process is not present in global stereopsis tests (Saladin 2005; Fricke & Siderov 1997).

An Example of a test for local stereopsis is the Titmus stereo test (Figure 5-1A). It consists of three subtests (the Stereo Fly test, the Circle test, and the Animal stereo test) and uses polarizing glasses at 40 cm distance. Random-dot stereograms tests for global stereopsis, are also known as cyclopean stereogram tests. The cyclopean form referred to the correctly fused two images and locally detected disparities without any monocular cue about the shape or depth of the form.

In 1960, Julesz introduced random-dot stereogram as a vision research tool (Julesz 1960). Many of the currently available stereoscopic tests are based on random-dot stereogram including TNO stereo test (Figure 5-1B), Frisby stereo test, Random-dot E stereo test, Randot test, and Lang lenticular-sheet stereo test. The interpretation of the results of these tests has to be done with caution as some people may lack the ability to focus correctly on the test stimulus and therefore find difficulty fusing the random-dot stereogram, despite the fact that they have a normal stereoscopic vision (Howard & Rogers 2002).

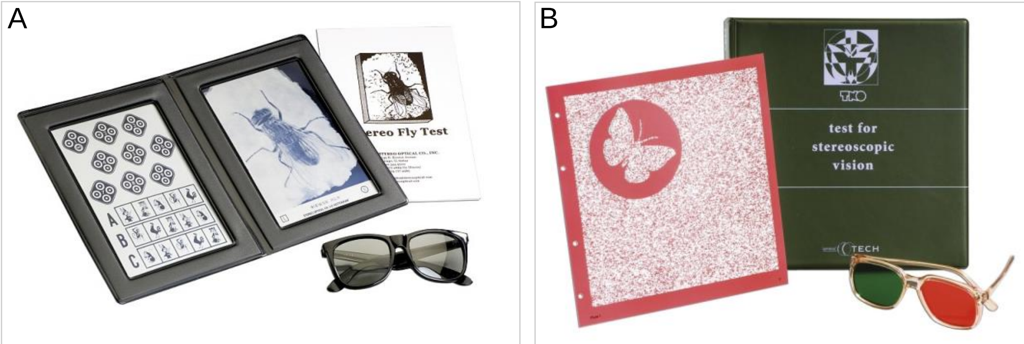


Figure 5-1 Examples of stereo tests. [A] Titmus Fly Stereo test for measuring local stereopsis. [B] TNO Stereo test for measuring global stereopsis. Images courtesy of : www.eyesfirst.eu

There are variations in the reported stereoacuity due to differences in the testing methodology, therefore, normative values are not clear cut (Zaroff et al. 2003). In general, clinically normal stereoacuity values are approximately 30-40 arc sec (McIntire, Havig, & Geiselman 2014; Fielder & Moseley 1996) and up to 50-60 arc sec (Lee & Koo 2005).

5.1.2 Functional significance

Stereopsis is one qualitatively distinct part of the whole depth perception experience; therefore, there is on-going debate about its functional impact especially in professions that heavily relay on high levels of visual abilities for skilled performance (e.g. aviation, MIS, dentistry) (Fielder & Moseley 1996; Snyder & Lezotte 1993; Waqar et al. 2012).

One major difficulty with investigating the role of stereopsis in real-world tasks is that binocular viewing confers a number of advantages. For example, a binocular view provides vergence[10] information that can be used to gauge the egocentric distance of a fixated target (Tresilian et al. 1999). Two eyes also

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[10] Simultaneous movement of both eyes in opposite direction to obtain single binocular vision.

enable a wider field of view and improved perceptual thresholds. This means that covering one eye to remove binocular vision does not provide an appropriate experimental manipulation for the purpose of establishing the contribution of stereopsis to a given task, and increases the difficulty in interpreting any decline in performance following this manipulation. As such, while there are a number of studies that have shown poorer performance on a variety of tasks under monocular viewing conditions (e.g. Wagner et al. 2012), these studies do not address the issue of the role played by stereopsis in the task. Some studies have shown the importance of stereopsis in real world tasks. These studies have compared the performance of individuals with and without stereo deficits on tasks involving manual dexterity. O'Connor et al. (O'Connor et al. 2010) showed that participants with normal stereoacuity had higher levels of performance on a pegboard and bead-threading task. Melmoth et al. (Melmoth et al. 2009) provided evidence that individuals with reduced stereoacuity have poorer coordination in reach-to-grasp movements (indexed by the reach kinematics). Moreover, Piano and O'Connor (Piano & O'Connor 2013) showed that degrading stereoacuity through the introduction of monocular refractive error (using spherical lenses to induce power difference so that one eye is more dominant) caused a decrease in manual performance within participants who had normal stereoacuity. The overall conclusion that emerges from these studies is that stereopsis does provide useful information that can be shown to support skilled performance in certain visuo-motor tasks.

5.1.3 Stereopsis and VR stereoscopic displays

Stereoscopic displays are the part of a VR system used to enhance the sense of immersion in simulated 3D VR environments (Held & Hui 2011) (see section

2.2). The enhanced interaction and immersion provided by stereoscopic displays is attributed to adequate field of view (FOV), increased awareness and enhanced depth perception via realistic depth cues that minimize the need for compensatory strategies to perceive depth (Lin & Woldegiorgis 2015; McMenemy & Ferguson 2007; Lewis & Griffin 1997).

Moreover, 3D stereo displays are especially useful in the performance of complex depth-related near tasks (e.g. spatial manipulations of objects), tasks involving distance estimation, navigation, detecting relative positions and objects (McIntire, Havig, & Geiselman 2014).

From a pedagogical perspective, the 3D stereo displays within the VR training environments, combined with skilled well-designed instruction, substantially contribute to spatial localization and comprehension of the anatomical structures and various surgical/dental procedures in a realistic presentation (Held & Hui 2011; Luursema et al. 2008).

Technically, in stereoscopic 3D displays there is a need for special eyeglasses to see the two slightly different stereo pairs (i.e. for stereo-channel separation: to direct the appropriate view to the correct eye and block the incorrect view to the opposite eye) and obtain the 3D sensation. Stereo-channel separation can be done with a variety of techniques including anaglyph/color-interlaced, polarization-interlaced, time-multiplexed, and head-mounted display. On the other hand, auto-stereoscopic display does not require any special glasses and the user can view the 3D scene directly (McAllister 2002; Geng 2013).

The increased adoption and constant improvements of 3D stereo displays and VR technologies in various applications including dental and medical training, assumes that the user/trainee has normal binocular vision and stereopsis

(Bradley et al. 2014). However, significant individual variations in depth perception exist when using stereoscopic displays (McIntire et al. 2014) which may be complicated by the presence of visual symptoms of eye strain, visual fatigue and discomfort either due to binocular visual deficits, or due to geometrical distortion of the stereoscopic display (e.g. crosstalk[11], binocular rivalry[12])(Lambooij et al. 2009).

Gadia et al. (2014) highlighted the importance of testing stereo acuity and stereo blindness prior to performance of critical tasks using stereoscopic displays (e.g. VR training) (Gadia et al. 2014). Trainees with deficient stereopsis may undergo totally different visual experience using 3D displays than trainee with normal stereopsis. This difference may manifest as accommodation problem (i.e., suppression, superimposition, binocular rivalry) and while they may adapt to such perceptual problems in real world (e.g.by utilizing monocular depth cues), they may not be able to do so in a virtual environment, particularly during task performance in near distance (Hale & Stanney 2006). Furthermore, some subjects with normal stereopsis may not perform well using stereoscopic 3D displays, phenomena that has been described as stereo anomaly and pseudo-stereo anomaly. This phenomenon has been attributed to deficits in fine vs. coarse stereopsis mechanisms which is based on the magnitude of horizontal disparities (McIntire, Havig, Harrington, et al. 2014).

[11] Incomplete isolation of the left and right image channels so that one leaks (leakage) or bleeds into the other. Also described as Ghosting.

[12] Visual perception phenomenon in which two different retinal images compete for the perceptual dominance.

5.1.4 Stereopsis and Surgical performance

In the surgical literature, the relation between depth perception and surgical performance has been explored by several studies particularly in relation to minimally invasive surgery as well as in general surgical training where fine motor skills acquisition is vital.

In ophthalmology, a review of literature highlights the lack of evidence to support stereopsis as necessary attribute to achieve acceptable skill levels in ophthalmic surgery. Stereo deficiency may be compensated by the use of other depth cues and by excellent manual dexterity (Elliott 2008). For example, experienced surgeons may utilize the movement of the surgical instrument (motion parallax perspective), relative size, texture gradient, and familiar anatomy to compensate for the lack of the third dimension (Wagner et al. 2012). In a study among a group of medical students, the stereoacuity levels were positively correlated with their initial performance scores on the Eyesi™ intraocular VR surgical simulator for cataract surgery, specifically at navigation and forceps training modules. However, it is unknown if this initial correlation would remain significant at more advanced stages of training (Selvander & Åsman 2011).

In minimally invasive surgery (MIS), the main challenge is to operate on 3 dimensional surgical sites via an indirect, restricted 2 dimensional monitor screen. This has a negative impact on depth perception and spatial orientation during performance. Currently, robotic-assisted laparoscopic surgery with 3D visualization has been increasingly used; it overcomes some of the disadvantages posed by the classical laparoscopic surgical technique (Blavier & Nyssen 2008) particularly the availability of stereoscopic depth information

(Held & Hui 2011). Therefore, depth perception, as a detrimental factor in MIS, has been thoroughly investigated in laparoscopic surgery training literature and its impact on performance.

Superior performance in 3D visual display and with robotic laparoscopy has been repeatedly reported. A study among medical students, with no previous experience in open or minimally invasive surgery, compared the surgical performance with regard to type of visual display used (2D vs.3D) and the type of surgical instrument (classical vs. robotic assisted laparoscopy). 3D visual display performance was found to be superior to 2D performance regardless of the surgical instrument used (Blavier & Nyssen 2008). Another study examined the effect of 2D vs. 3D visual display while performing three different laparoscopic surgery tasks among participants with varying laparoscopic experience. Each task was performed in open performance (direct), in 3D visual display using (The EndoSite 3Di simulator), and using the DaVinci® robotic system. The same tasks were repeated using an eye patch simulating monocular vision. Three-dimensional vision significantly impacted the performance regardless of the participant’s experience, task difficulty, or the surgical settings used (Wagner et al. 2012). Similar findings have been reported in another study using Fundamentals of Laparoscopic Surgery (FLS) skill set in 2D and 3D visual display among participants with various range of surgical experiences (Tanagho et al. 2012).

In contrast, Mistry et al. (2013) showed that training performance of surgery naïve medical students on the McGill Inanimate System for Training and Evaluation of Laparoscopic Skill (MISTELS) using Monoscopic (2D) visualization displays was the same as or better than performance under stereoscopic (3D) visualization. This has been attributed to the inherent difficulty of the tasks that were beyond the students' skill level and to the possible role of increased cognitive load with stereoscopic visualization during training (Mistry et al. 2013).

Equal performance was reported for subjects who have normal stereopsis and those with no stereopsis in 2D visual display (video-assisted) laparoscopic surgical simulator. However, in binocular direct view tasks (3D visual display), stereo-absent participants perform worse than those with normal stereopsis, although the level of stereoacuity didn't correlate with task performance (Bloch et al. 2014). Similarly, no correlation was found between the level of stereoacuity and performance of simulated surgical tasks using VR laparoscopic simulator (Hoffmann et al. 2015). Collectively, despite the wide range of reported findings, there is substantial evidence to support the stereopsis role in performance of fine surgical tasks particularly in robotic laparoscopy under 3D visualisation.

5.1.5 Depth perception in dentistry

Good visual perception is also paramount to the practice of dentistry. It is a highly visual professional field that involves working in a limited small-scale environment and performing fine skilled manipulations that require high degree of hand-eye coordination and attention to fine detail in tenths of millimetre (e.g. tooth preparation depth) . Therefore, not only is visual acuity important but also other visual attributes such visual depth perception, contrast sensitivity and colour vision (Wasson & Schuman 1992; Gokce et al. 2010; Mushtaq et al. 2016). Depth perception in dentistry enables the dentist not only to visually perceive depth but also to precisely judge position, estimate distances and correct sizes during dental performance (Dimitrijevic et al. 2011). Moreover, good visual acuity and depth perception are important assets in clinical diagnosis of dental caries, in estimation of correct convergence of the crown preparation, in oral radiography interpretation and to control the depth of various cavity preparations (Arruda et al. 2008; Wenzel 1999; Nick et al. 2009; Ricketts et al. 1995).

Dental literature has focused mainly on visual acuity and colour vision of dentists with only few studies on visual depth perception. Additionally, limited research has explored the relation between vision quality and dental performance. Currently, studies have explored the effect of vision enhancement through magnification on dental performance (Bowers et al. 2010; Perrin et al. 2014; Eichenberger et al. 2013; Maggio et al. 2011; Eichenberger et al. 2015).

When a comprehensive vision screening has been conducted among undergraduate dental students, several visual defects have been reported including defects in visual acuity, squints, limited convergence, and defective stereopsis (with four students exhibited no stereopsis using the TNO stereo test). None of the screened students were aware of their visual deficiencies and were referred for treatment (Rawlinson 1988).The same author continued the vision screening program of undergraduate dental students for a further six years. The same visual defects reported previously in addition to defects in colour vision were consistently found among all studied cohorts. The inability of some students to complete the dental course or the difficulty in passing exams didn’t correlate with their results in the visual screening. Therefore, it has been concluded that minor correctable visual defects are not critical to the successful completion of dental study and hence their use as predictor of performance was not supported (Rawlinson 1993).

Another study assessed dental students’ vision and track visual changes longitudinally for four years during dental school. The students have been screened for near and distance visual acuity (with and without correction), colour vision, ocular movements, and stereopsis. The results of the baseline assessment revealed that 23% of the students had deficits in one or more of the screened visual components and none of them were aware of it. Minor colour deficiency was detected in10% of the students, heterophoria (an ocular condition in which one or both eyes tend to wander away from the position where both eyes are looking together) in 8%, and less than normal stereopsis in 5% of the screened students (Green et al. 2011; Green et al. 2013). Nevertheless, no data has been reported on the effect of these visual deficiencies on performance in dental school.

Forgie and colleagues screened a group of practicing dentists in Scotland for visual acuity, convergence, accommodation, contrast sensitivity, heterophoria and stereoscopic vision. The results showed an overall accepted values of visual standards and recommended regular eye examinations for dentists. They indicate that although 10% of the examined dentists had no stereopsis (stereo blind) and/or defective stereopsis, they were capable of successful clinical performance (Forgie et al. 2001).

5.1.5.1 Stereopsis and dental performance

An earlier study (Ireland et al. 1982) explored the specific role of stereopsis in dental psychomotor learning and whether it can predict student performance. The results of the TNO stereo test were compared to students' performance in preclinical operative dentistry course. The study found that students with low level of stereoacuity still performed well in the course, suggesting the use of other depth cues (e.g. monocular depth cues). Therefore, it has been concluded that a high level of stereopsis is not a prerequisite to acquire dental fine motor skill.

In oral radiology, dental students have been trained to use stereovision and radiographic depth interpretation to compose 3D image from two radiographs (using the buccal-object rule). The training was done using a single image colour field stereogram and classical stereograms of circles. Their visual acuity as well as stereopsis was measured and 5% showed no stereopsis. Students who accurately composed the 3D images achieved better diagnostic performance for third molar localization and root deviation than those who couldn't compose the 3D image (Wenzel 1999).

Early student performance on a manual dexterity training aid (Learn-A-Prep II - LAP II) was compared to their performance in subsequent practical examinations (class II amalgam preparation and complex amalgam preparation). The depth aspect of (LAP II) performance was only predictive of practical performance early in the course. It has been suggested that normal stereoacuity level and good depth perception may have contributed to the early acceptable preparation depth. Through subsequent training, handpiece-handling skills have been developed resulting in more precise control of the preparation, therefore augmenting the depth perception skills (Boushell et al. 2011). Another study examined the ability of dentists and dental students to estimate depth and reproduce small distances during performance using three experimental tasks (depth perception task, distance task, and writing task).

The results were compared to participants' stereopsis level, dental performance and practical experience. Experienced dentists have better accuracy in performing the three tasks, albeit not significantly, and inexperienced students (early in this course) performed poorly. Inexperienced students tend to overestimate depth and distance and this tendency improved with practical experience. The participants' stereoacuity scores did not correlate with their depth estimation or with the students' grades. The authors highlighted the fact that although depth estimation is influenced by the degree of depth perception but they are not the same (Dimitrijevic et al. 2011).

So far, the converging evidence supports the role of depth perception in dental performance, however, the specific role of stereopsis in dentistry is not supported and debated as well.

5.1.5.2 Virtual reality dental simulators

Despite the importance of depth perception in dental practice, there has been some debate regarding the particular importance of stereopsis in dentistry. A recent review of literature didn't support the functional significance of stereopsis in dental training and concluded that defective or absent stereopsis is not a hindrance to dental practice and, therefore, should not be considered a prerequisite to dental training (Syrimi & Ali 2015). However, these conclusions have been questioned subsequently by Mon-Williams et al. (Mon-Williams et al. 2015) based on the fact that the paucity of available evidence from dental literature about the role of stereopsis does not necessarily preclude its significance. Since stereopsis is task specific, there is a need to explore its role in dental tasks that are particularly dependent on depth perception (e.g. cavity preparation). They highlight the need for empirical evidence regarding the significance (or not) of stereopsis in dentistry particularly at this time where virtual reality simulators (with stereoscopic displays) are being increasingly adopted in dental training (Mon-Williams et al. 2015).

The intuition that stereopsis might be important in dentistry is reflected in the design of dental surgical simulators which provide realistic haptic feedback and 3D rendered images for the purpose of training. There is no doubt that the provision of 3D stereovision provides a powerful and realistic rendition of the oral cavity. Nevertheless, there are no data to support the inclusion of such perceptual information within the design of these surgical simulators (i.e. there is no evidence to demonstrate that dentists actually use stereo information to carry out dental procedures). The existence of such simulators does, however, provide a unique opportunity to address the fundamental issue of whether stereopsis has a functional role within dentistry. The Simodont® simulator presents an opportunity to examine this question as it can be engineered to provide a full binocular experience with or without stereoscopic viewing. This enables a robust investigation into the impact of removing stereoscopic information whilst keeping the other visual features of the display constant.

As the debate continues about the functional significance of stereopsis in dentistry, it is imperative to investigate the topic empirically, particularly in relation to three main aspects : the experience of the operator (dental student or dentist), the complexity of various dental tasks and procedures, as well as the performance setting (dental clinic, virtual simulator, or phantom head simulator).

Drawing upon those three main aspects, this chapter has set out to investigate the role of stereopsis in dentistry from two different perspectives. Therefore, two studies were conducted, each with a distinct experimental approach and participants, to answer a specific set of questions about the role of stereopsis in dental performance.

5.2 SECTION ONE: Investigating the role of stereopsis in dental performance using VR haptic simulator

5.2.1 Aims and objectives

This study aimed to measure the impact of removing stereopsis within the stereoscopic display in Simodont® VR simulator (whilst leaving other information unaffected) on the performance of postgraduate dentists in standard dental tasks.

It is hypothesised that the removal of stereopsis should cause more performance errors in depth if stereopsis has a functional role in fundamental dental skills.

Therefore, using the VR haptic dental simulator Simodont®, the objective of the current study is to explore how the performance of postgraduate students is affected by:

a) *Viewing conditions*: stereoscopic (3D visual display) and non-stereoscopic (2D visual display).
b) *Task difficulty:* represented by two viewing orientations (direct and indirect via virtual dental mirror).

5.2.2 Methods

5.2.2.1 Participants

Sixteen participants (13 female and 3 male, mean age = 32.8 years, *SD* = 3.5 years), with at least three years of clinical experience, but no previous experience of using a dental VR simulator, participated voluntarily in the study following email announcement and personal communication by the researcher.

The participants were postgraduate dental students from various dental specialities (Paediatric dentistry, prosthodontics, periodontics, oral biology and oral surgery) completing their studies at the School of Dentistry, University of

Leeds (see Chapter 3, section 3.2.2). They have no history of ophthalmological or neurological disorders and have normal or corrected vision and their stereoscopic acuity was measured using StereoTAB test, (described in the following section). All participants completed an informed consent, were fully debriefed and were clearly informed that their participation has no impact on their academic marks as all data are anonymised and the study has been conducted independently from their studies.

Ethical approval was obtained from DREC (Dental Research Ethics Committee) at the School of Dentistry, University of Leeds (DREC ref: 230915/LA/178).

5.2.2.2 Stereoscopic Acuity Test

To ensure that the participants had access to stereo-information before exploring whether removal of such information has an impact on real-world performance, stereoacuity was measured using StereoTAB v3.0.4. (Vallejo 2014), This is a random-dot based stereo test presented as a digital automated application specifically designed for measuring global stereopsis (in seconds of arc) at near and long distances.

It is a non-invasive, simple and quick (2-3min) test that requires the use of anaglyph eyeglasses (red/cyan or red/green). It uses pictures of stereo figures that are embedded in a background of random dots. The StereoTAB test was reported to be a sensitive test with good discriminative power and correlated well with the TNO stereoscopic test (Poças 2016; Vallejo et al. 2014).

The test was delivered using an iPad 2 (Model number A1395). The iPad was placed at table top in front of the participant, stabilized with a tripod stand (size: 22x8.5x2 cm) with distance of approximately 1m as specified in the application settings and the participant wore anaglyph eyeglasses (red/cyan) with red filter on the left eye. The experimental setup for testing stereoacuity is illustrated in Figure 5-2.

A descending staircase procedure was used, whereby the stereoacuity level gradually decreased with each new stimulus. Once the application is opened, the finest procedure button is selected, then a random dot pattern appears in the centre of the screen with a hidden shape (⅙ sliced circle) oriented in one of four possible orientations (up, down, left or right) depending on the missing slice position. If the participant cannot identify the hidden shape the question mark button can be pressed and new shape will appear. On the other hand, if the participant identifies the hidden stimulus the corresponding button (with matching shape) can be pressed at the button bar. Next, a new hidden random shape will appear with a lower level of stereoacuity. The same procedure continued (screen 10 levels of stereoacuity) until the results appear on the screen with the recorded stereoacuity measurement obtained by the participant.

The minimum binocular disparity measurement depends on the pixel size of the device used (Vallejo 2014). In our experiment an iPad 2 Retina was used, and it is 40 arc sec for the finest stereopsis. There are 10 possible arc sec measurements that could be recorded: 40, 79, 119, 159,199, 238, 278, 318, 357, 397. The lower the measurement the better the stereoacuity, therefore, values above 100 arc sec were considered as stereo deficient.

The stereoacuity test is used in the current study as a screening test only and is not diagnostic, and this was made clear to all participants.

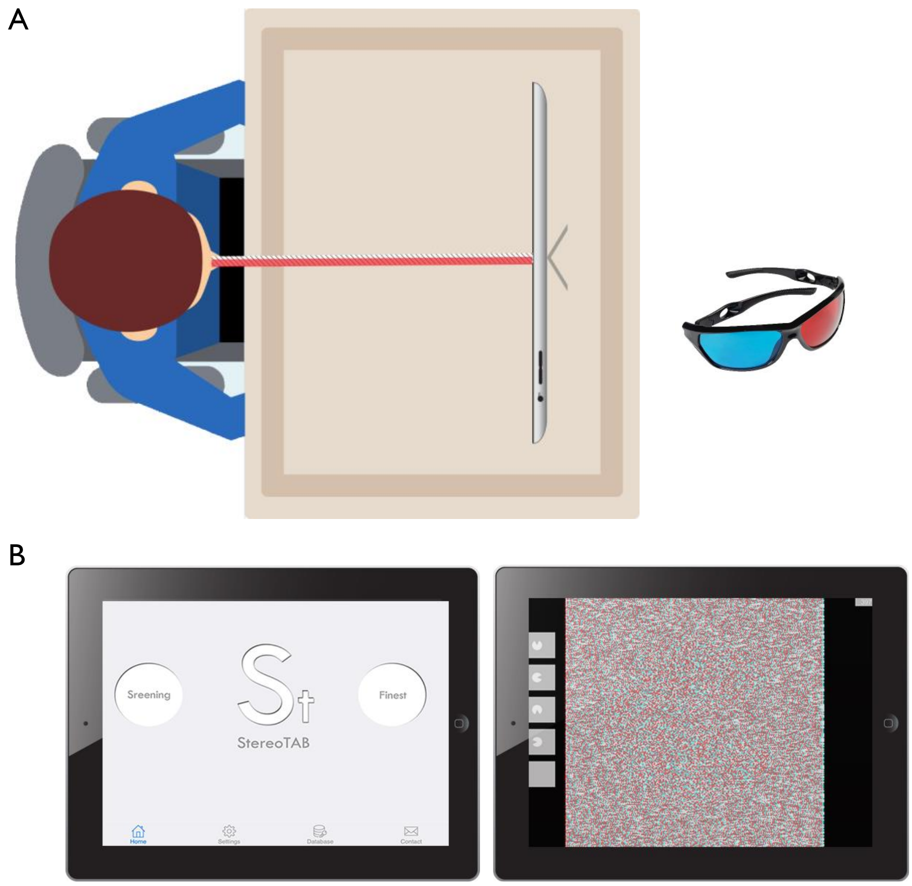

Figure 5-2 [A] Schematic illustration of the experimental setting used in the current study for testing stereoacuity, and the anaglyph glasses (red/blue) used during the test, the red line represent the participant-iPad distance (≈ 1m). [B] An iPad 2 with (Stereo TAB) application interface, and the test interface.

5.2.2.3 Experimental tasks

Each participant performed four different tasks from the manual dexterity module in Simodont®. The tasks were two basic abstract shapes with minimal geometric difference (Figure 5-3). The rationale of choosing the two slightly different shapes is to ensure that the performance is not due to a practice effect (i.e. performing the same shape four times) and at the same time to ensure that both shapes are not markedly different in geometry, which may add a difficulty factor that is not intended in the current experiment.

Participants performed each task with two viewing orientations: directly viewing the shape and indirectly via a virtual dental mirror (Figure 5-3C). Participants were instructed to cut as much of the target region as possible whilst minimizing/avoiding drilling into the leeway and the container regions.
The participants were able to freely move (rotate and tilt) the test block (abstract shape) with control handle located beneath the display screen, so that it is possible for them to access the target area conveniently (as it is possible in a real clinical case where the patient position can be adjusted to access the tooth to be treated).

To avoid any confounding order effects, the task shape order was counterbalanced[13] as well as the task viewing orientation among participants.

[13] A method for controlling the order effect in repeated measures study design.

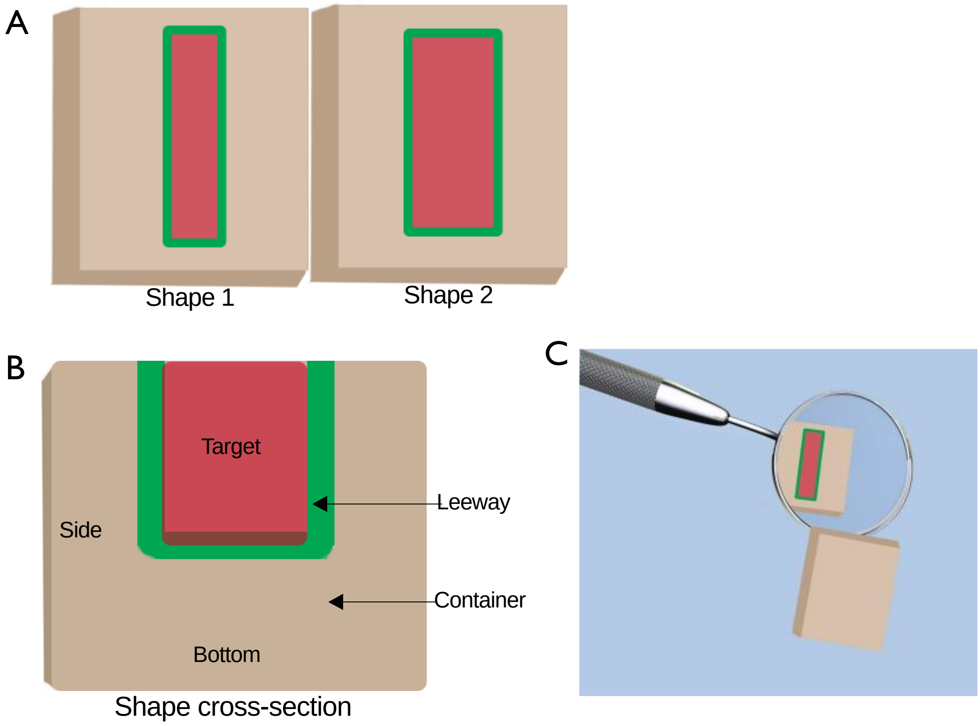

Figure 5-3. Schematic illustrations of the manual dexterity tasks used in the current study available from the Simodont® courseware [A] Top-view of the abstract shapes used in the experimental tasks. [B] Side view with cross-section shows the different regions of the abstract shape. The sides and bottom of these regions comprised the error metrics for laterality and depth, respectively. [C] Reflected abstract shape via virtual dental mirror used in the indirect view tasks.

5.2.2.4 Experimental protocol

The experiment was conducted at the Simodont® Skill Laboratory at the School of Dentistry, University of Leeds. The stereoacuity level of the participants was measured using the StereoTAB application. Afterwards, the participants were introduced to the Simodont® haptic dental simulator with a short overview, followed by a demonstration of the simulator and testing procedure. Each participant was allowed to try out the device as part of the introduction, to familiarize themselves with the procedure and the required task (Figure 5-4). Each participant then started to perform the experimental tasks in the order specified by the investigator. The target removal percentage of 60% was considered acceptable, once reached; the participant can stop cutting the shape and the task ends. After each task, the performance measures were recorded. In the stereoscopic tasks, the participant wore polarized passive 3D glasses provided with the simulator. While in the non-stereoscopic conditions, the participant were provided with non-polarized lightly tinted eyeglasses, in order to minimize the differences between the two viewing conditions and to avoid the light intensity difference that may affect performance.

At completion, participants received a debrief sheet, outlining the aims of the study and the researcher contact details, should they have further questions at a later time, or should they wish to withdraw their data at any stage.

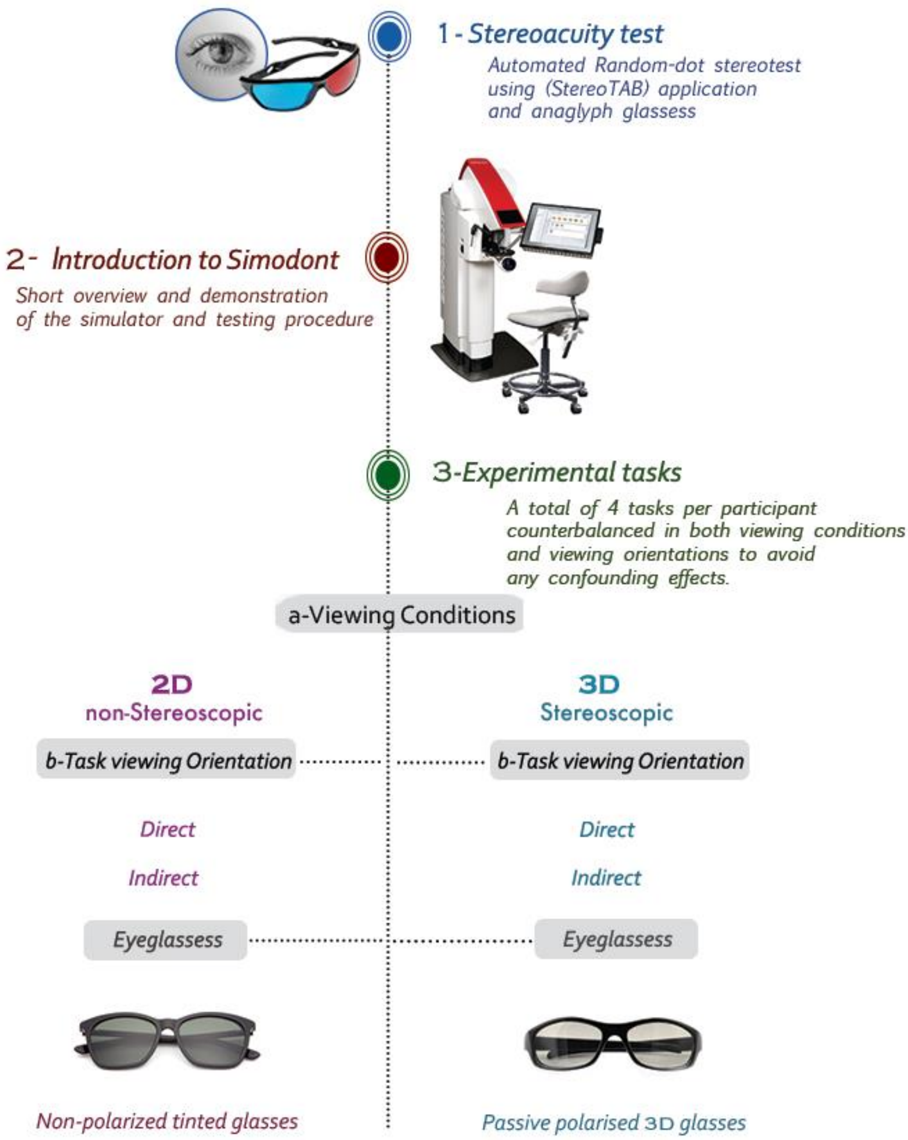

Figure 5-4 Experimental protocol used in the current study.

5.2.2.5 Data collection and statistical analysis

This is a cross sectional quantitative study with repeated measure design. Dental task performance was captured using the metrics provided automatically by the simulator: error scores (Leeway and Container-see Figure 5-3B) for the sides and the bottom of the abstract shape, and the task completion percentages. For this study, we were primarily concerned with the amount of depth related errors made by participants within each condition. To this end, we used a composite score of the amount of depth error in the leeway bottom and container bottom regions of the abstract shape (quantified as the volume prepared/cut as a percentage of total surface area) to identify depth error (DE). We also calculated the total error scores made by the participant at two other specific areas of the abstract shape- the leeway and container sides to produce a composite score for lateral error (LE). Finally, the percentage of total surface area removed (provided by the simulator as task completion %) was used as Target Area Removal (TAR) measure.

Each dependent variable was subjected to a two (Type of Vision [2D vs. 3D] X two (Orientation [Direct vs. Indirect]) repeated measures ANOVA. All data were tested for departures from normality by boxplot, Q-Q plots, histograms and Shapiro-Wilk's test with transformations performed where necessary (container lateral scores before calculating the composite lateral scores).

The statistical significance threshold was set to $p < 0.05$. Bonferroni-corrected post hoc comparisons were performed where significant main effects were found. Partial eta squared values ($\eta_p{}^2$) were reported to indicate effect size. All statistical analyses were performed using IBM SPSS® Statistics for Windows (Version 22, Armonk, NY: IBM Corp., 2013).

5.2.3 Results

5.2.3.1 Stereoacuity results

All participants exhibited stereoacuity values within the normal range (40-79 arc sec). However, two participants showed abnormal results (one was unable to detect any stimulus in the StereoTAB test, and the other participant scored 318 arc sec and was considered stereo deficient but in the current sample is an outlier). Although both continued the experimental protocol, we decided later to exclude them from the final data analysis and therefore, the total sample size is reduced to 14 participants.

5.2.3.2 Depth errors (DE)

The effect of the type of visual display (3D stereoscopic/2D non-stereoscopic) used to perform the tasks on DE was statistically significant, F (1,13)= 9.539, p= 0.009, η_p^2 =0.42, with mean drilling error being higher for the non-stereoscopic viewing condition (M = 20.62, SE = 2.78) compared to stereoscopic (M=13.77, SE=2.32); with statistically significant mean difference of 6.843, 95% CI [2.057, 11,629] (Figure 5-5 A). These results indicate that participants were drilling too far in the non-stereoscopic viewing condition.

On the other hand, the effect of task orientation on DE was not significant, F (1,13)=0.024, p=0.880, η_p^2 =0.002, with comparable mean depth errors values for direct (M = 17.24, SE = 2.76) and indirect orientation (M = 17.16, SE = 2.78) (Figure 5-5B).

The two-way interaction between visual display manipulations and orientation on DE was not statistically significance, F (1,13)= 2.728, p = 0.12, η_p^2 = 0.17.

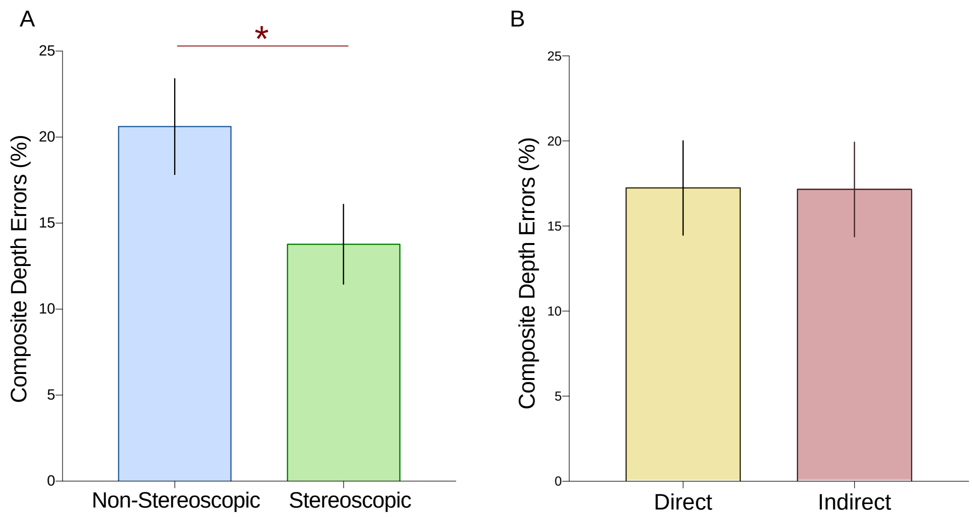

Figure 5-5 Composite Depth errors (DE) in [A] non-stereoscopic and stereoscopic visual display conditions; [B] direct and indirect viewing conditions. Error bars represent ± 1 S.E.M. Red star denote statistical significance.

5.2.3.3 Lateral errors (LE)

In contrast to DEs, the effect of the type of visual display (3D stereoscopic/2D non-stereoscopic) used to perform the tasks had no statistically significant effect on the amount of LEs made by participants (Figure 5-6A), F (1,13)= 0.152, p= 0.703, $\eta_p{}^2$ = 0.012.

In addition, there was no effect of orientation (D/ID) on LEs, F (1,13)= 0.502, p= 0.491, $\eta_p{}^2$ = 0.037 (Figure 5-6B). The two-way interaction between visual display manipulations and orientation on LE was also not statistically significance, F (1,13)=0.567, p= 0.465, $\eta_p{}^2$ = 0.042.

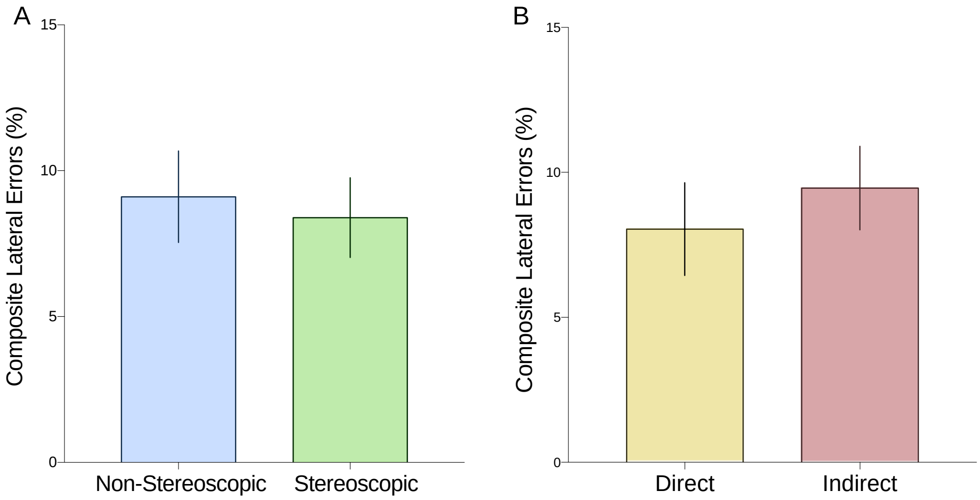

Figure 5-6 Composite Lateral errors (LE) in [A] non-stereoscopic and stereoscopic visual display conditions; [B] direct and indirect viewing conditions. Error bars represent ± 1 S.E.M.

5.2.3.4 Target area removal (TAR)

The effect of the type of visual display (3D stereoscopic/2D non-stereoscopic) did not significantly influence the total amount of TAR (Figure 5-7A), F (1,13)= 1.729, p= 0.211, η_p^2 = 0.117.

However, reflecting the expected difficulties associated with indirect tasks, we did find a significance of orientation (Figure 5-7B). F (1,13)= 4.973, p= 0.044, η_p^2 = 0.277, with higher mean TAR scores for direct observation (M=68.24, SE= 1.39) compared to indirect (M=65.22, SE= 0.97), and a statistically significant mean difference of 3.021, 95% CI [0.095, 5.948].

The two-way interaction between visual display type and orientation on TAR did not reach statistical significance, F (1,13)= 4.01, p= 0.067, η_p^2 = 0.236.

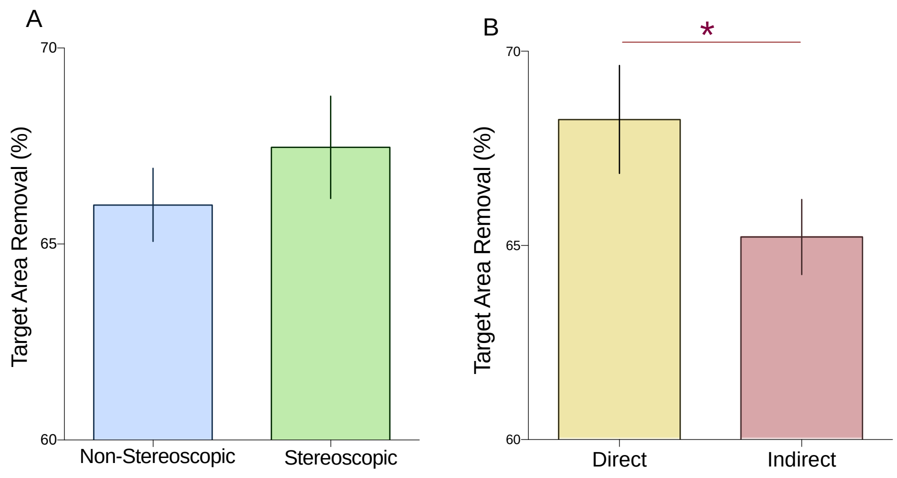

Figure 5-7 Target area removal (TAR) scores in [A] non-stereoscopic and stereoscopic visual display conditions; [B] direct and indirect viewing conditions. Error bars represent ± 1 S.E.M. Red star denote statistical significance.

Table 5.2-a Means (± *SD*) for all the performance metrics recorded in the current study under the 4 experimental conditions. (N=14).

		Non-stereoscopic display		**Stereoscopic display**	
		Direct	***Indirect***	***Direct***	***Indirect***
Performance Metrics	**TAR** *Target area removal (%)*	66.79 (± 3.8)	65.21(±3.9)	69.7(±8.3)	65.24(±4.7)
	DE *Depth errors composite (%)*	9.2(±6.02)	11.4 (±7.14)	8.03(±4.9)	5.7 (±5.4)
	LE *Lateral errors composite (%)*	4.11(±3.13)	4.9(±3.9)	3.9 (±4.04)	4.5(±3.6)

5.2.4 Discussion

In this study, we investigated the role of stereopsis in basic simulated dental task performance among postgraduate dentists. The data showed that the dentists benefitted from the presence of stereovision. Importantly, we demonstrated that the presence of stereovision decreased the preparation errors in depth but not the lateral errors. This allows confidence that the experimental manipulation was specific to the hypothesized role of stereopsis (i.e. improving depth perception) rather than a general decrease in performance induced by unusual viewing conditions.

One of the main factors that contribute to the superiority of stereoscopic 3D visual display conditions over 2D, during performance is the enhanced distance perception (Lin & Woldegiorgis 2015) which is valuable information in fine motor task performance.

The current findings are consistent with the results of an earlier study (de Boer et al. 2016a) using Simodont® where novice dental students showed superior performance in manual dexterity exercises under 3D stereoscopic relative to 2D non-stereoscopic visual display conditions, however, unlike our study, their participants wore the 3D polarized glasses in both viewing conditions which may contribute to the reported eye discomfort in 2D visual display conditions.

Our findings also showed a reliable effect of task view orientation, with lower target area removal in the indirect (mirror) condition made when compared to direct condition. This is not surprising because indirect tasks (performed with mirror vision) are inherently more challenging and impose additional task challenges in terms of hand-eye coordination, dental mirror positioning and hand piece control.

We were interested to see whether there was a two-way interaction between the visual display conditions and task orientation on the performance metrics. In fact, we found no statistically reliable interaction on any of our measures. The lack of an interaction may be due to the small sample size, however, the results do suggest that the largest effects on performance are driven by the presence or absence of stereo information and the task complexity.

The participants with normal stereoacuity have presumably refined their dental skills on the basis of this information being available. It is possible that individuals with long-term stereo-deficits may learn to use other sources of information (e.g. the knowledge of dental anatomy, or the use of gauging instrument as periodontal probe) and thereby avoid a reliance on stereopsis. This possibility has been explored within previous research exploring the role of stereopsis in reaching-to-grasp (Grant et al. 2007) where it was found that individuals with permanent stereo-deficits show performance decrements (i.e. these individuals were not able to compensate for their stereo-deficits). There is a need, however, to determine whether it is possible to compensate for long-term stereo-deficits in dental skills. This will require the identification of qualified dentists with stereo-deficits and comparing their performance with dentists who have normal stereoacuity.

One participant in the current study was unable to identify the stereoscopic stimulus in the stereo test (i.e. unable to detect any visible edges in the random dots background) despite that we repeated the test after a five minute break. This could be explained as deficient or completely absent stereoscopic acuity, or possibly the participant has otherwise normal stereopsis but was unable to respond to the test stimulus due to differences in depth cues perception that is not optimal for this particular test (Saladin 2005; Howard & Rogers 2002). Confirming either case is beyond the scope of the current study, however, this was explained to the participant and they were reassured that this test is not intended to diagnose any visual condition and it is employed in the current study for screening purposes only. The participant continued the experiment with no difficulty in any of the experimental conditions.

The present findings also have implications for the design of VR dental simulators. There has been an assumption that stereovision is an important feature of such simulators. The data presented here provide empirical support for this assumption.

Further issues that need careful consideration in simulator design more broadly are the fact that the types of monocular cues typically available in natural environments which can compensate for stereopsis (e.g. shadows) are not fully simulated in VR simulators. Additionally, the presence of ghosting (i.e. crosstalk or the incomplete isolation of the left and right image channels so that one leaks (leakage) or bleeds into the other) on the projection screen could also impact on performance (McIntire et al. 2014; Lin & Woldegiorgis 2015). The fact that dentists are learning to use stereopsis to control their actions suggests that simulators should ensure the perceptual information used in training maps to the information available in the ‘real world’. We therefore argue that simulators should, for example, control for inter-pupillary distance (e.g. via calibration) to ensure that disparities are rendered accurately within the displays. Discrepancy between the inter-pupillary distance of the trainee and the inter-ocular distance of the display will lead to eyestrain or visual fatigue (as a result of defective accommodation and binocular fusion)

(Lewis & Griffin 1997; Lambooij et al. 2009) and subsequently may result in reduced performance.

Finally, since dental tasks vary widely in terms of their complexity, it is likely that this will affect the need for stereoscopic information for successful performance. In the current study, the tasks were basic manual dexterity exercises that were controlled in terms of the standardized settings within which the removal of the target area is performed. The shape was positioned evenly in the participant's view and was presented in a uniform virtual block with no adjoining dental structures. It seems reasonable to assume that the role of stereopsis will increase as the perceptual-motor demands of the task increase (Fielder & Moseley 1996; Bloch et al. 2014; Piano & O'Connor 2013). The fact that we found an effect of removing stereopsis in relatively simple tasks indicates the fundamental role for stereopsis in dentistry.

5.2.5 Conclusion

The performance of simulated tasks in haptic virtual reality dental simulator was optimized under stereoscopic 3D visual display conditions. The presence of stereovision decreased the preparation depth-related errors but not the lateral errors. The data confirm that the participating dentists used stereopsis and its presence resulted in improved performance.

It remains to be determined whether individuals with stereo-deficits can compensate adequately. Nevertheless, these findings suggest an important role for stereopsis in dentistry and justify the design of simulators with 3D stereoscopic displays.

5.3 SECTION TWO: The Correlation between Stereoscopic Acuity and Dental Performance among Undergraduate Dental Students

5.3.1 Aims and objectives

This study aimed to investigate the association between undergraduate students' stereoscopic acuity and their practical dental performance in preclinical operative dentistry.

Therefore, the objectives of the present study are:

1- To measure the level of stereoacuity among a group of undergraduate dental students.

2- To explore the correlation between the stereoacuity and dental performance represented by final practical test results in two preclinical training settings:

   a) Preclinical Laboratory 1: using virtual reality haptic dental simulator (Simodont®).

   b) Preclinical Laboratory 2: using Phantom head simulator.

5.3.2 Methods

5.3.2.1 Participants

A group of undergraduate dental students (N=28, 18 female and 10 male) from third year dentistry program at the School of dentistry, University of Leeds, participated voluntarily in the study following an email announcement and personal communication by the researcher. All participants completed an informed consent sheet, were fully debriefed and the study was approved by Dental Research Ethics Committee at the School of Dentistry, University of Leeds (DREC ref: 230915/LA/178).

5.3.2.2 Stereoscopic Acuity Test

Stereoacuity of the participants was measured using StereoTAB test (detailed description in section one, section 5.2.2.2).

5.3.2.3 Preclinical dental performance

The students' dental performance results were obtained from the student education office and from the module leaders. The Simodont® results (for each trial done by each student) were accessed via the Simodont® server, downloaded, filtered, arranged in Excel sheets, calculated and exported to SPSS for analysis. Confidentiality was maintained by assignment of code numbers replacing students name. For each participant, a total of 4 final grades were obtained and calculated as follow:

A. ***Result 1 (Preclinical VR Simodont® laboratory):***

These are the average results of students practice on manual dexterity exercises available in the Simodont® courseware (by ACTA). Due to the large number of trials performed by each student for different exercises and due to differences in number of trials per student, we standardize the selection criteria in the current study as follow: the number of trials included per student is 30 and the task completion level is 60% and above.

B. **Result 2 (Preclinical Phantom head simulator laboratory):**

a. *Phantom1 (Year 2):* Spotter test results performed in the phantom head using typodonts. In this laboratory test, the students are asked to spot the wrong/defective part of a preparation or restoration. Afterwards, a final mark out of

100 is assigned to students based on their performance by the instructor.

b. *Phantom 2 (Year 2):* The average of continuous assessment (CA) practical exercises, graded on scale of 4 (Excellent, Acceptable, Below acceptable, Fail). A total of nine exercises, each exercise consists of two tasks: cavity preparation and restoration using amalgam, composite or resin modified GIC (Table 5.3-a).

c. *Phantom 3 (Year 3):* The result of full crown preparation test on typodont plastic teeth at year 3.

Table 5.3-a Continuous assessment (CA) exercises (phantom lab) at year 2 of dental school.

Restorative material	Preclinical exercise
Resin Composite	• Occlusal Cavity Preparation and Restoration • Posterior Approximal Cavity Preparation and Restoration
Amalgam	• Occlusal Cavity Preparation and Restoration • Approximal Cavity Preparation and Restoration
Resin Composite	• Anterior Approximal Cavity Preparation and Restoration • Incisal Corner Cavity Preparation and Restoration
Resin modified glass ionomer cements (RMGIC)	Cervical Cavity Preparation and Restoration
Amalgam	Large Cavity Preparation and Restoration
Resin Composite	Large Cavity Preparation and Restoration

5.3.2.4 Data collection and statistical analysis

This is a cross-sectional study using a quantitative methodology. Preliminary analyses showed that all continuous variables (test results) were normally distributed, as assessed by Shapiro-Wilk's test ($p > .05$), and there were no outliers. For the ordinal variables, preliminary analysis showed the relationship to be monotonic, as assessed by visual inspection of a scatterplot.

The stereoacuity results were coded as stereo normal and stereo deficient based on the obtained measurement. To explore the performance of the students in each test based on their stereoacuity measurement, independent sample t-test was run for each assessment. A Mann-Whitney U test was run for the preclinical continuous assessment test (ordinal variable).

Spearman's rank-order correlation test was run to assess the relationship between stereoacuity and students' performance at the three tests (Crown, Spotter, and Simodont®). A Goodman and Kruskal's gamma correlation test was run to assess the relation between stereoacuity (two codes) and phantom continuous assessment results (four codes) because both variables were ordinal.

Linear regression analyses were run to explore the relationship between stereoacuity and performance at the three tests (crown, spotter, and Simodont®). Additionally, an ordinal logistic regression with proportional odds was run to determine the effect of stereoacuity on phantom CA performance.

The statistical significance threshold was set to $p < 0.05$. All statistical analyses were performed using IBM SPSS® Statistics for Windows (Version 22, Armonk, NY: IBM Corp., 2013).

5.3.3 Results

5.3.3.1 Stereoacuity test results

Most participants (78.6%) exhibited normal stereoacuity within the range of 40-60 arc sec. Other participants (21.4%) scored 159 arc sec and above in the StereoTAB test, and recorded as stereo deficient.

Mann-Whitney U test was run to determine if there were differences in stereoacuity levels among male and female students. Distributions of stereoacuity levels were similar, as assessed by visual inspection. Median stereoacuity was not statistically significantly different between males and females (Figure 5-8), $U = 88$, $z = -0.135$, $p = 0.944$.

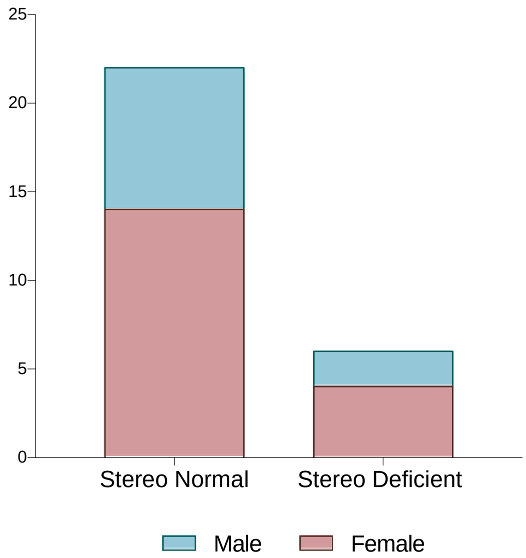

Figure 5-8 Stereoacuity distribution among male and female students (N=28).

5.3.3.2 Stereoacuity and practical dental performance

A. Group differences

An independent-samples t-test was run to determine if there were differences in test scores between stereo normal and stereo deficient students. There were no outliers in the data, as assessed by inspection of a boxplot. Exam scores for each level of stereoacuity were normally distributed, as assessed by Shapiro-Wilk's test ($p > 0.05$), and there was homogeneity of variances, as assessed by Levene's test for equality of variances ($p = 0.33$).

Stereo deficient participants performed slightly better ($M = 78.83$, $SEM = 3.628$), in the typodont crown test than stereo normal ($M = 76.23$, $SEM = 2.898$). However, the mean performance difference between the two groups $M = 2.6$, 95% CI [-14.745, 9.533], was not statistically significant, t (26) = -0.441, $p = 0.66$, $d = 0.22$ (a small effect size according to Cohen1988).

For the *Phantom 1 Spotter test*, comparable performance of both groups were reported for stereo normal ($M = 71.77$, $SE = 2.35$) and stereo deficient ($M = 70.67$, $SE = 4.34$) participants, so the mean performance difference between the two groups $M = 1.11$, 95% CI [-9.25, 11.46], was not statistically significant, t (26) = 0.219, $p = 0.83$, $d = 0.10$.

In the *Simodont® test*, performance scores for stereo deficient group was higher ($M = 79.67$, $SE = 2.32$) than stereo normal group ($M = 76.8$, $SE = 0.94$), however, this difference did not reach statistical significance, and the mean performance difference is $M = -2.85$, 95% CI [-7.28, 1.56], t (26)

= -1.33, p = 0.19. d = 0.56 , a medium effect size according to Cohen (1988).

For the *Phantom 2 results (preclinical continuous assessment),* Mann-Whitney U test was run and revealed a similar distribution of the test scores for both groups as assessed by visual inspection. Median Test scores were not statistically significantly different between stereo normal (mean rank = 14.14) and stereo deficient (mean rank = 15.83) participants, U = 74, z = 0.52, p = 0.68. The performance of both groups on all four tests is shown in Figure 5-9.

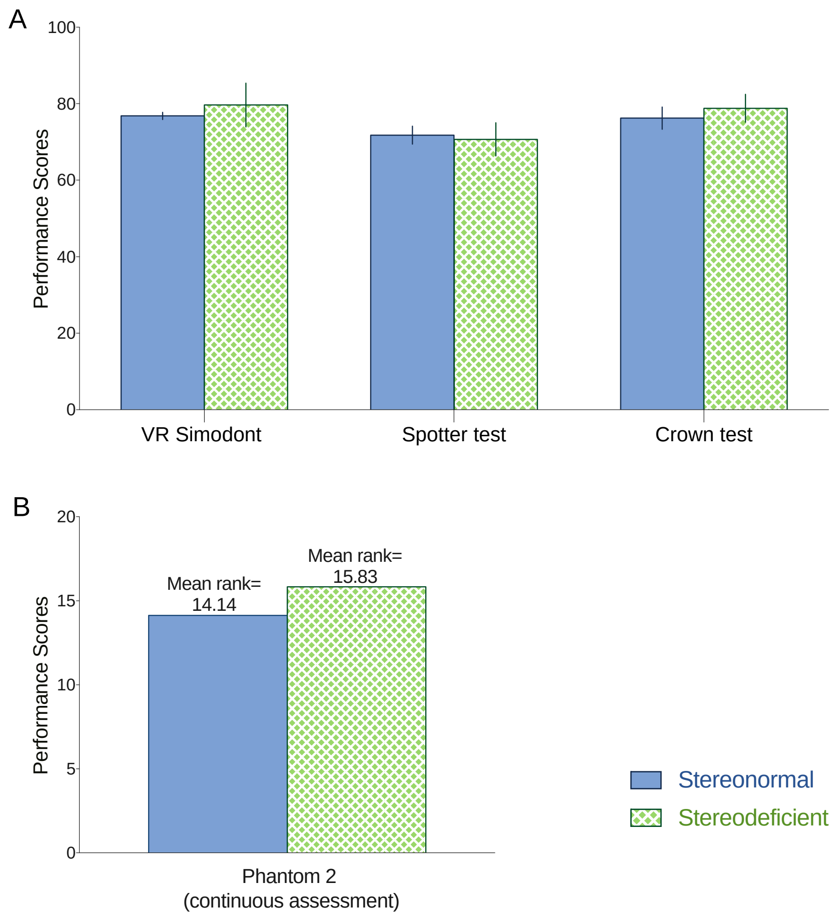

Figure 5-9 The performance of stereo normal and stereo deficient students in the practical assessment. [A] Mean and SEM (error bars) of the preclinical tests. [B] Mean rank of the preclinical phantom continuous assessment results.

B. Correlation analyses

Spearman's rho tests showed no significant correlation between stereoacuity and any of the three practical test results (Simodont® test, spotter test, and crown test), $p > 0.05$ (Table 5.3-b).

Similarly, Goodman and Kruskal's γ test revealed a non significant small positive correlation (G= 0.25, p= 0.58) between stereoacuity and phantom two results (CA).

Table 5.3-b Spearman's rank-order correlation (r_s) between stereoacuity and students performance (N=28).

	Spearman's rho correlation coefficients with Stereoacuity	***p-value***
Simodont® VR Test	0.248	0.203
Phantom Spotter Test	-0.060	0.763
Phantom Crown Test	0.076	0.702

Correlations significant at p < 0.05.

C. Regression analyses

- **Linear regression**

Regression analyses showed that there was no evidence (p >0.05) of a significant predictive relationship between a participant's stereoacuity and their preclinical practical performance.

For the phantom spotter test, stereoacuity level did not predict the student performance significantly F (1,26)= 0.048, p= 0.83. Stereoacuity accounted for only 0.2% (R^2= 0.002) of the variation in the performance with adjusted R^2 value of - 0.037.

Similarly, for the typodont crown test, stereoacuity level did not predict the student performance significantly F (1,26)= 0.067, p= 0.79. It accounted for only 0.3% (R^2= 0.003) of the variation in the performance with adjusted R^2 value of - 0.036.

Although for the Simodont® VR assessment, stereo acuity level also did not predict the student performance significantly F (1,26)= 1.76, p= 0.19; however, it accounted for 6.4% (R^2= 0.064) of the variation in the VR performance with adjusted R^2 value of 0.028, much more than the performance variations in the two phantom tests.

- **Ordinal logistic regression**

Ordinal logistic regression with proportional odds was run to determine the effect of stereoacuity levels (dichotomous) on phantom CA performance (ordinal). The deviance goodness-of-fit test indicated that the model was a good fit to the observed data, χ^2 (1) = 1.358, p = 0.24. However, the final model did not statistically significantly predicted the phantom CA performance over and above the intercept-only model, χ^2 (1) = 0.181, p = 0.67.
The odds ratio of being in a higher category (excellent) of the dependent variable (Phantom CA) for stereo normal versus stereo deficient participants is 1.475 95% CI [0.273, 7.982], a statistically non-significant effect, χ^2 (1) = 0.203, p = 0.65. Therefore, the stereoacuity level did not have a statistically significant effect on predicting the phantom CA performance Wald χ^2 (1) = 0.203, p = 0.65.

5.3.4 Discussion

The majority of participants in the current study exhibited normal stereoacuity values, however, about 21.4% showed deficient stereo acuity according to the StereoTAB test. Moreover, the students' performance in four different preclinical operative dentistry assessments did not correlate significantly with their stereoacuity.

Stereoacuity values were a non-significant/weak predictor of student preclinical performance. These findings are consistent with previous studies in the dental literature (using TNO stereo test) (Ireland et al. 1982; Rawlinson 1993; Dimitrijevic et al. 2011) which did not find any association between undergraduate dental students performance and their stereoacuity measurements. Of note are the differences in the reported prevalence of stereo deficiency among dental students in the current study and other studies (5%(Green et al. 2011) , 7%(Dimitrijevic et al. 2011) , and 23% (Rawlinson 1993)) as well as among other groups (Coutant & Westheimer 1993; Biddle et al. 2014; Selvander & Åsman 2011) . Although some studies have reported complete loss of stereopsis among some dental students (Rawlinson 1993), and dentists (Forgie et al. 2001) this was not found in our sample of undergraduates.

In the current study, stereo deficient students performed as good as and even slightly better than stereo normal students in preclinical continuous assessment, typodont crown test and Simodont® assessment, however this trend did not reach statistical significance. Similar trend has been reported previously in the surgical literature where stereo impaired or stereo blind participants performed better than stereo normal group in some, but not all, experimental tasks (Barry et al. 2009; Waqar et al. 2012; O'Connor et al. 2010). Such trends emphasise the multidimensional nature of depth perception particularly during performing fine intricate tasks that depends on the interaction of many different physical, neurologic, cognitive and sensorimotor attributes. Moreover, the stereo deficient participants who are at the 3rd year of dental school possibly are still able to sufficiently perceive depth (albeit not optimally due to impaired stereopsis) via compensatory mechanisms such as monocular depth cues (e.g. relative size, shadows, and aerial perspective). Furthermore, it is interesting to know, not only from our study but also from other stereopsis-screening studies in the dental and surgical literature, that subjects who have impaired stereopsis did not know about their visual anomaly before the test. This implies that, unlike other visual deficits, stereopsis is a quality of binocular vision that enhances our visual experience but when it is absent, we are still able to navigate satisfactorily in the visual world using other compensatory depth cues.

Such results draw our attention to the fact that the level of dental performance cannot be attributed to a single factor *per se* such as stereoscopic acuity. The complexity of dental procedures demands a more focused approach to investigate the possible effect of stereoscopic acuity particularly at task level (Fielder & Moseley 1996; O'Connor et al. 2010) where the subtle influences become more evident and identifiable. Dental tasks vary widely in terms of complexity and the need for three-dimensional information for successful performance. The following factors are suggested which might potentially affect clinical task performance in some operative dental procedures (that need special attention to fine detail). These can be grouped as dentist and task related factors.

Dentist factors

- Cognitive attributes and scientific knowledge
- Hand-eye coordination
- Visual acuity
- Manual dexterity and sensorimotor skills
- Stress/fatigue

Specific task factors

- Type of dental treatment (preventive, restorative, prosthetic, surgical)
- For operative procedures:
  - ~ The accessibility and the position of the tooth in the dental arch (maxillary, mandibular, anterior, or posterior)
  - ~ The ability to control the oral environment (i.e. moisture control, isolation with rubber dam)
  - ~ The level of task complexity (e.g. full PFM crown preparation on upper second maxillary molar, or simple class I resin composite restoration on lower first molar)
  - ~ Level of task details needed (e.g. measuring depth, length or the width of the cavity or the tooth, locating root canal orifices or applying layers of different restorative materials in confined small part of the tooth).

Such factors and many others should be carefully considered when designing future studies for stereopsis investigation in dentistry. Additionally, future studies should explore longitudinally how the stereo deficient students will thrive in dental school, and whether they find some procedures particularly difficult to perform successfully.

Although our findings are in line with previous dental literature, this should not rule out the functional significance of stereopsis in dentistry. Rather, it should be a catalyst to fine-tune the future research approaches to this topic by focusing on individual dental tasks and how critical stereoscopic acuity is to its successful performance.

5.3.5 Conclusion

The majority of undergraduate dental students in our sample exhibited normal stereo acuity values, however, about 21.4% showed stereo deficiency. No significant correlation was found between stereoacuity and students' preclinical performance in virtual reality and conventional simulation settings. Therefore, stereoacuity is considered a weak predictor of student preclinical performance in the current study. Further research focusing on the effect of stereoacuity on performance at task-level is warranted particularly among larger cohorts of dental students.

Chapter 6 : Feedback and motor skill acquisition using a haptic dental simulator

Feedback can be broadly described as the information received during or after an action, event or process that form the basis for improvement (Magill 2011). The feedback provided to learners about their performance is in the heart of any learning cycle, and it has been identified as the most important feature that promotes effective learning in simulation-based education (Issenberg et al. 2005; McGaghie et al. 2010). In simulation-based dental education, the learning of sensorimotor skills in simulation laboratories is a fundamental part of the dental curriculum particularly at the preclinical stage. It provides a safe learning environment with the availability of feedback and support from dental educators in a structured training setting.

The technological advances in medical and dental simulation methodologies and the increased adoption of high fidelity simulators based on VR technology emphasised the central role of feedback in pedagogy by introducing special types of performance feedback, such as visual and auditory feedback (Scalese et al. 2008). Additionally, kinematic measurements are automatically recorded in these simulators that convey precise quantitative information about the learner's motor abilities during simulated task performance (Suebnukarn et al. 2009). This unique feature of VR simulators is not available in the more traditional physical simulators, that do not provide any degree of interactivity with learner's input, and it is qualitatively different from the information conveyed in an instructor's feedback, therefore adding another dimension to the performance assessment that was not accessible before.

In the wider pedagogical context, feedback in technology-assisted instruction comprises the information conveyed to the learner via a variety of sources (e.g. verbal, display) following his/her input, aiming to shape the learner's perception, cognition or action (Shute 2008). Whatever the source of performance feedback, its ultimate goal should be to enhance learning and that is very much dependant on the content of the feedback, and how it is optimally utilized in specific learning contexts.

Due to the importance of sensorimotor skill learning in dental education, understanding the role of feedback from the motor skill acquisition perspective is vital to promote effective skill learning in simulation settings and beyond.

In the context of motor skill learning, performance is differentiated from learning as being a transitory change in motor action observed during practice. Learning can be only evaluated after practice, specifically through retention or transfer tests (Shumway-Cook et al. 2012).

Performance feedback is defined as all the information the learner receives as result of a movement or practice of motor skill. It provides guidance to achieve the correct movement or the desired skill level. It has both informational and motivational influence on motor skill learning (Wulf et al. 2010; Wulf & Schmidt 2014).

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 (Baker & Young 1960; Gordon 1968; Hester et al. 2010; Wolpert et al. 2011; Yousif & Diedrichsen 2012; Mushtaq et al. 2013).

6.1 Types of feedback

Feedback can be broadly classified, based on its source, into intrinsic or extrinsic.

- Intrinsic feedback: it is the sensory perceptual information provided naturally, as a result of an individual's movement, through exteroception (i.e. vision, audition), and proprioception (i.e. from mechanoreceptors in the skin, proprioceptors in the muscles and joints that provide information about movement, location and velocity) (Proctor & Dutta 1995; Magill 2011).
- Extrinsic (augmented) feedback: is the additional information provided by an external source such as a person/instructor or a device through various modalities (single or combined) such as visual (e.g. screens, head-mounted display), auditory (e.g. speakers, headphones), and haptic (i.e. through tactile and kinaesthetic input that provide information about certain features of the task).

Augmented (extrinsic) feedback is commonly categorised based on its information contents into :

1. **Knowledge of result (KR):** information about the outcome of the performance only, with no specific information about what aspects of the movement contributed to the outcome. In the conventional preclinical dental skill training environments (using phantom head simulators), terminal feedback (KR) is typically provided by an instructor when the student completed all or part of the dental task (e.g. cavity preparation) (Feil et al. 1986).
2. **Knowledge of performance (KP):** information about the quality of performance and movement characteristics in terms of kinetic (i.e. forces applied during performance) and kinematic information (i.e. temporal and spatial properties of the movement) both of which contribute to performance dynamics that resulted in the outcome

(Proctor & Dutta 1995). Such information is not available in a conventional dental training environment.

Augmented feedback can be delivered at different timings, and at various frequencies. It can be provided during performance (concurrent, on-line), or at the end of performance (terminal feedback) and it could be immediate or delayed (Tresilian, 2012; Sigrist et al., 2013). Feedback frequency refers to how frequent the performance feedback is available to the learner. It could be continuous (100% frequency) after each trial, intermittent (reduced frequency after a set of trials) or fading feedback (reduced frequency of feedback overtime) (Sigrist et al. 2013). Additionally, bandwidth feedback (when errors exceed certain defined limits) and self-controlled (the learner decides when to access the feedback and through which modality) has been described (Wulf & Schmidt 2014).

6.2 Feedback in motor skill learning .. Help or Hinder?

The effect of feedback on motor skill learning is dependant on multiple factors such as the complexity of the skill, the feedback frequency, contents, timing, the learner's experience, and the learner's focus of attention (Shea & Wulf 1999; Wulf & Schmidt 2014).

The theoretical underpinning of the role of feedback in motor skill learning can be explained on the basis of the guidance hypothesis (Salmoni et al. 1984) and the cognitive load theory (Sweller 1988).

Concurrent and frequent feedback was found to be detrimental in simple skill learning. It has been shown that feedback presented frequently during simple motor skill acquisition, provides guidance to the learner about the important features of the learned skill and enhance performance during training and acquisition phases. However, the performance declines in no-feedback conditions, because the frequent concurrent feedback produced dependency on the external information and interrupted the intrinsic representation of the task, thereby negatively impacts on the long-term learning (Sigrist et al. 2013), this has been described as the guidance hypothesis (Salmoni et al. 1984). Delayed terminal feedback is found to promote error estimation and detection by the learner, provided that the learner is familiar with target performance goal (i.e. not in the early acquisition phase), but this process can be interrupted if concurrent and immediate feedback is provided (Sigrist et al. 2013; Wulf & Schmidt 2014).

In contrast, the more complex the skill the more useful the concurrent feedback is to the learner, as it prevents cognitive overload by guiding the learner to the most effective strategies to perform certain movements. It directs the attention of the trainee to the relevant aspects of the skill and facilitates understanding of the underlying processes required to complete a difficult motor task thereby contributing to the development of accurate motor representations and facilitating the learning of the complex skill (Wulf et al. 1998; Sigrist et al. 2013; Sigrist et al. 2015). The majority of research supports the positive effect of concurrent feedback in complex motor skills learning (Sigrist et al. 2013; Shea & Wulf 1999; Wulf & Shea 2002; Huegel & O'Malley 2010).

The cognitive load theory (Sweller 1988) focuses on the information processing in learning and how the capabilities of the working memory handle the mental effort associated with new information/tasks, providing a framework for effective instructional design. The information overload associated with a new task or learning conditions can negatively impacts the limited capacity of the working memory, however when the new information is structured into defined units (cognitive schemas) that can be conveniently processed and stored in the long-term memory, the cognitive load is reduced and the learning is facilitated. The cognitive load can be intrinsic (i.e. related to the characteristics and nature of the task), or extraneous (i.e. related to how the task or task-related information is presented). Germane cognitive load is the effort required to organize the new information into cognitive schemas in the long-term memory. Both extraneous and germane cognitive loads can be changed by instructional design, and the optimal instruction that would facilitate learning should reduce the extraneous cognitive load, thereby enhancing the creation of cognitive schemas in the long-term memory (Sweller et al. 1998; Sweller 1988; Hatala et al. 2014).

In motor skill learning, explanation of the task by an instructor facilitates its understanding and therefore reduces the learner's cognitive load (Hatala et al. 2014). Additionally, specific feedback (KP**-** Knowledge of performance) information (i.e. prescriptive feedback) provided concurrently about critical movement pattern and how to correct errors, particularly to beginners /novices, prevents the cognitive overload therefore enhances the learning of complex skills that require high levels of coordination (Magill 2011; Wulf & Shea 2002). During motor skill acquisition, augmented feedback facilitates the association between the intrinsic feedback (e.g. proprioception) and the goal of the learned task, resulting in better recall of the learned task and maintained performance that depends on intrinsic feedback alone during no-feedback situations (i.e. real task performance) (Anderson et al. 2001).

6.3 Performance Feedback in Simulation-based education

The availability of Knowledge of result (KR) feedback during simulated practice has been identified as one of the most important factors that leads to effective learning (Sigrist et al. 2013; Shea & Wulf 1999; Wulf & Shea 2002; Huegel & O'Malley 2010).

Virtual reality simulation technologies offer an opportunity to present on-line continuous feedback on surgical performance through presentation of visual and auditory information (Scalese et al. 2008). With the introduction of haptic VR simulators, sensory (tactile) feedback become available 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.

6.3.1 In medical and surgical education

Multiple sources of feedback during motor skill training in surgical simulation-based education has been shown to consistently result in superior performance compared to single feedback source/modality, particularly for immediate post-tests (Hatala et al. 2014). For novice trainees in endovascular skill training, VR feedback resulted in general improvements in performance in difficult tasks and skill acquisition was further accelerated through the introduction of expert instructor-guided feedback (Boyle et al. 2011). Similarly, the availability of instructor feedback in VR laparoscopic complex skill training has resulted in increased learning efficiency (Strandbygaard et al. 2013) although this did not affect the long-term retention of the learned skills (Bjerrum et al. 2015). On the other hand, for suturing skill performance retention, verbal expert feedback was found to be superior to simulator generated feedback with and without expert reference values in junior medical students (Porte et al. 2007).

The timing of feedback was found to impact on the surgical skill learning, as terminal feedback is reported to be superior to concurrent feedback for retention of simple skills in novices (Hatala et al. 2014). Novice endoscopists who received terminal feedback during training on a colonoscopy simulator task outperform those who received concurrent feedback at a transfer test (Walsh et al. 2009). Novice medical students trained with concurrent feedback, terminal feedback, or video based instruction practice settings performed equally in the acquisition of basic surgical skill, however, at retention test, only terminal feedback and video based instruction groups retained their performance level (Xeroulis et al. 2007).

6.3.2 In dental education

In the dental literature, the use of VR simulators for undergraduate operative dentistry training was found to be effective in providing objective formative evaluation, and in enhancing skill acquisition rates (Buchanan 2001).

The role of feedback in dental preclinical training has also been investigated in conventional (Feil et al. 1986), computer-assisted (Wierinck et al. 2005) and VR environments (Suebnukarn et al. 2010; Rhienmora et al. 2009). 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 (Feil et al. 1986).

In a series of experiments, Wierinck et al. explored the role of augmented feedback from a computer-assisted/augmented reality simulator (DentSim) on skill acquisition (Wierinck et al. 2005; Wierinck et al. 2006a; Wierinck et al.

2006b). The simulator provided 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 skill retention (Wierinck et al. 2005). In another study, standardised expert input provided at a tutorial session, before the students completed a task, was found to be more beneficial for retention and transfer of skill than VR feedback alone (Wierinck et al. 2006b). Suebnukarn et al. (2010) showed that the availability of augmented kinematic feedback, about variations of movement pattern by the haptic VR simulator whilst performing an endodontic access preparation, enhanced student performance at the early stages of skill acquisition and retention (Suebnukarn et al. 2010).

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. Therefore, the type of feedback of interest in the current investigation is augmented feedback (both knowledge of result and knowledge of performance) and how it impacts the learning of simulated basic dental tasks. This augmented feedback is specifically obtained from two extrinsic sources: dental educator (verbal) and VR haptic dental simulator (visual, haptic).

6.4 Aim and Objectives

Predicated on the existing research, the aim of the current study was to examine the contributions of augmented 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 handpiece 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)

(c) long-term changes in learning (retention).

6.5 Materials and Methods

6.5.1 Participants

Sixty-three participants (13 male and 50 female, 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. The participants were undergraduate university students studying at various faculties/schools (except Dentistry) at the University of Leeds. They 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.

6.5.2 Devices

6.5.2.1 Simodont®

Participants were trained and tested on the Simodont® VR haptic dental simulator. For full simulator description (see Chapter 3, section 3.2.1).

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).

Table 6.5-a Kinematic performance measures provided by the Simodont®

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

6.5.2.2 CKAT

In order to ensure equivalence in underlying motor abilities in our sample, the clinical kinematic assessment tool - (CKAT; (Culmer et al. 2009)) an objective measure of motor control - was used to assess motor ability at baseline.

The CKAT is a specialized software system for measuring detailed hand movements. It is designed to operate on a commercially available tablet, with the tablet stylus as the main input device that measures the planar position of the stylus tip on the laptop screen. In the current study, Toshiba tablet (Toshiba Portégé, 14″ screen: 260 × 163 mm, 1,280 × 800 pixels, 32 bit colour, 60 Hz refresh time) was used to run the KAT system (Figure 6-1). It delivers inter-active kinematic assessment trials in which a computerised series of manual fine motor control tests objectively record hand movements in details using accurate and repeatable measurements from standardised three visual-spatial tasks across a range of subtests including tracking, sequential aiming and tracing tasks in fixed order. Automated data analysis functions are integrated within the CKAT system and run after each trial to quantify performance metrics. The data processing steps and task requirements for the battery are described in more detail elsewhere (Flatters, Mushtaq, et al. 2014; Flatters, Hill, et al. 2014).

A B

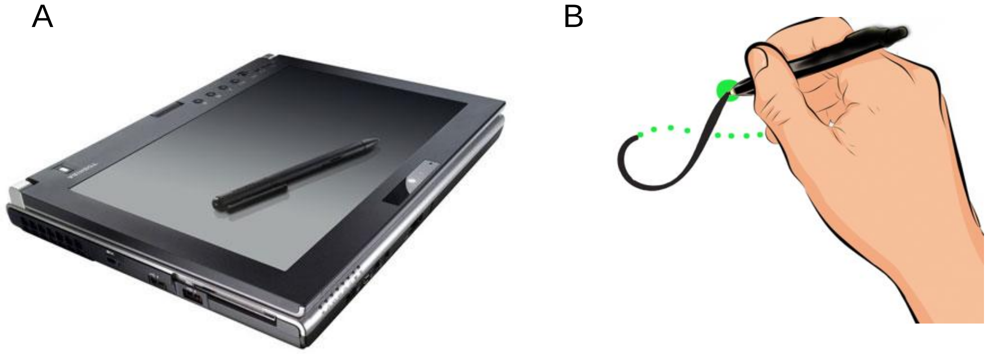

Figure 6-1 [A] The Toshiba tablet (with stylus pen) used to run CKAT system in the current study (Model Toshiba Portégé M700 Series). [B] Schematic drawing of an example of dot-tracking task in CKAT, the participant has to follow the moving green dot and keep the stylus on the screen all the time.

6.5.3 Simodont® Tasks

Five different geometric shapes, available in two different depths (0.4mm and 0.8mm) were employed in this experiment. A schematic example of one of the shapes (cylindrical) is shown in (Figure 6-2A).

Each shape consisted of three zones (Figure 6-2B): (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. Furthermore, the participants were informed that the acceptable target removal percentage of all tasks in the current study was 70%. Operational definitions of the performance measures are shown in **Table 6.5-b**.

Table 6.5-b 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 6-2B) and were computed as a percentage of the total region (leeway/bottom)

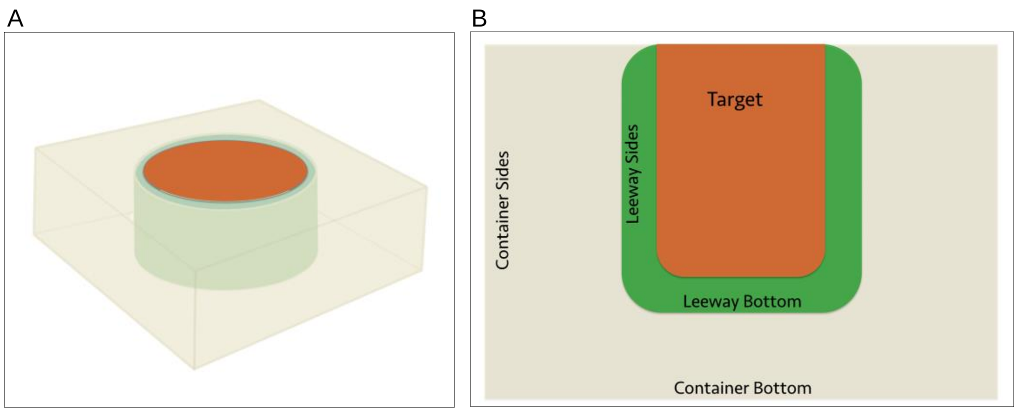

Figure 6-2 [A] Schematic drawing of one of the abstract shapes available in manual dexterity training module of Simodont® courseware; [B] Cross-section of the abstract shape (3 coloured zones).

6.5.4 Procedure

Initially, the participants' motor skills were assessed with the CKAT. After completing the CKAT test, 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 6-2B) and avoid going beyond the shape boundaries. All participants were allowed to try out the device (2-3 minutes) as part of the introduction to familiarize themselves with the procedure and the required task. Next, a baseline skill (BL) assessment was conducted, and the 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 6.5-a).

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 was concurrent and 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 practised 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 conditions. No specific time limit was set to complete each task, however, all participants in all groups spent an average of 30 seconds to 1.5 minute per task.

The experimental protocol is illustrated in Figure 6-3**.**

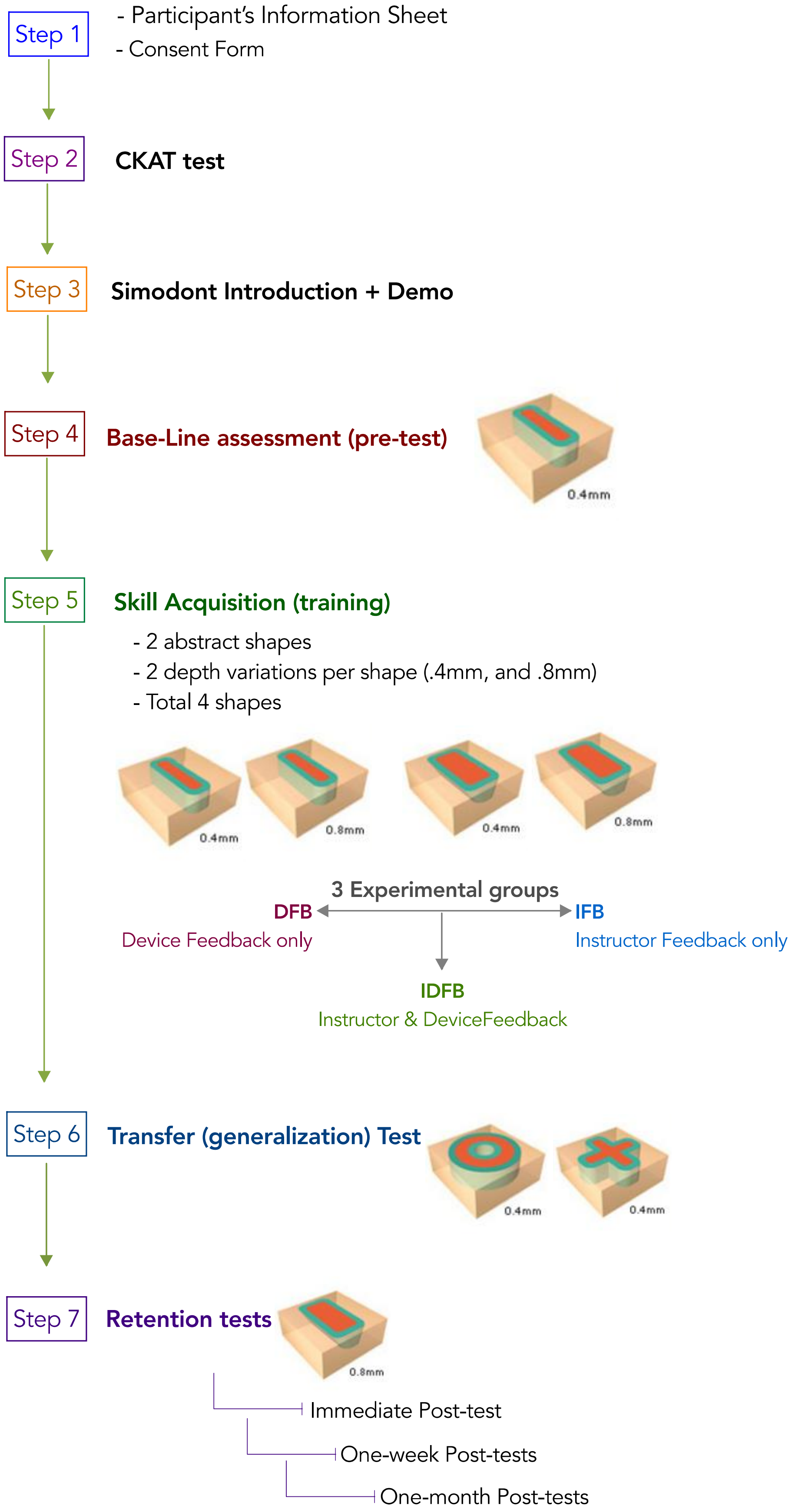

Figure 6-3 Experimental protocol of the current study.

6.5.5 Data collection and statistical analysis

CKAT performance was analysed using R statistical software (R Development Core Team, 2010); The arithmetic mean of the tracking, aiming and tracing tasks composite scores were calculated to give the overall test score for the C-KAT. A detailed analysis methodology is described by Flatters et al. (2014).

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.

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. 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;
- Transfer a 3 (Group) x 2 (Transfer Test 1 vs. 2) ANOVA;
- Retention, a 3 (Group) x 3 (Time; Immediate vs. Week vs. Month) ANOVA.

Gender differences were investigated using independent-samples t-test for all performance measures at baseline, training, transfer and retention phases.

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[14] 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).

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[14] Sphericity is an important assumption for repeated measure ANOVA analysis. It indicates that the differences between all combination levels of the within-subjects factor must have equal variances. When violated, an adjustment (to the degree of freedom- DOF) is required so that it retains valid results (p-values) (Martin & Bridgmon 2012).

6.6 Results

6.6.1 Overall Simodont® composite error scores

The overall Composite error scores were significantly different among the groups, [F (2,60) = 5.63, p = 0.006, η_p^2 = 0.158] with the IDFB having significantly lower error scores (M = 13.68, SD = 5.6) than DFB (M = 21.4, SD = 9.6) (Figure 6-4).

There was no statistically significant difference between male and female participants in the overall composite error scores, [t (61) = -1.464, p = 0.148].

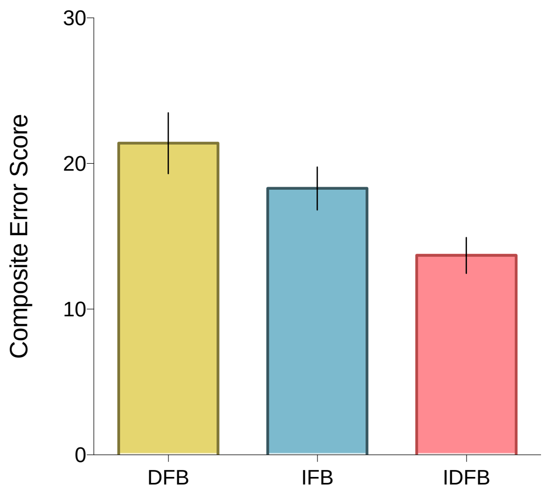

Figure 6-4 The overall composite error scores among the 3 feedback groups: [DFB] Device Feedback group, [IFB] Instructor Feedback group, [IDFB] Instructor Device Feedback group. Error bars represent ±1 SEM.

6.6.2 Performance at baseline test (Pre-test)

At baseline (BL), there were no significant differences (F's < 2.86, p's > 0.065) 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 (Figure 6-5). Similarly, no significant differences were found in any of the performance measures between male and female participants (t's < 1.274, p's > 0.21) at baseline (Figure 6-6).

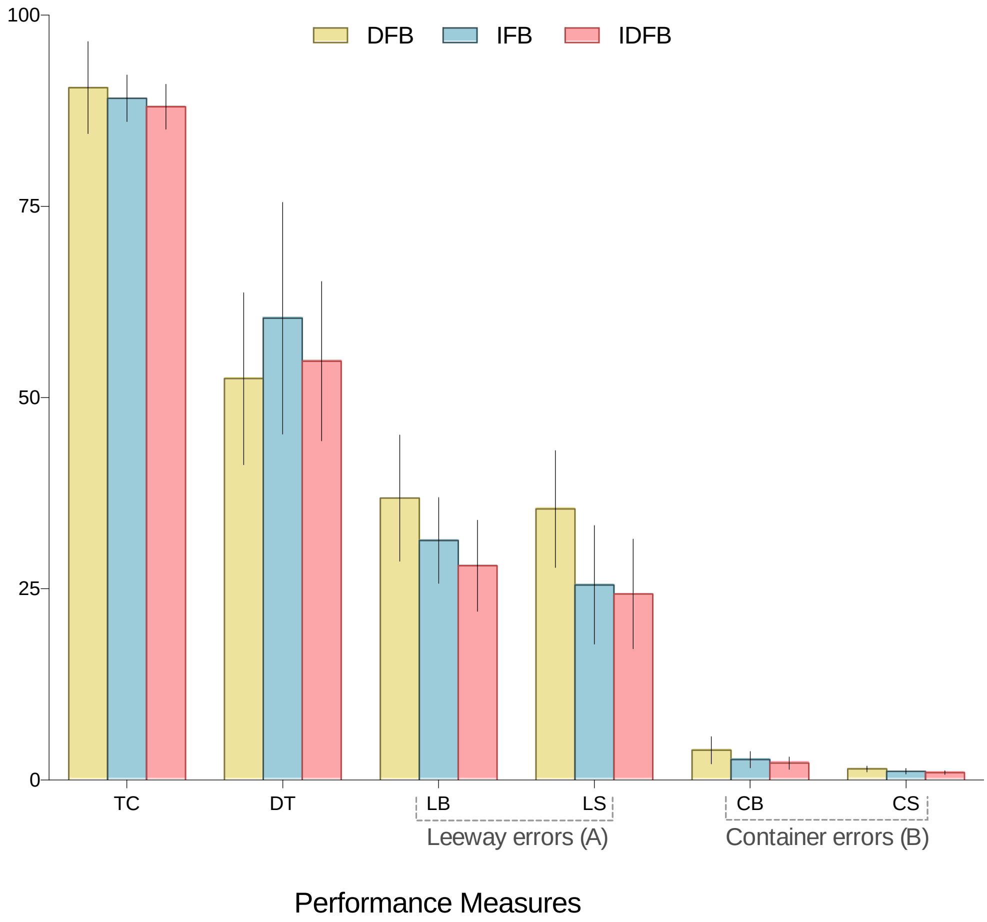

Figure 6-5 Performance measures among the 3 feedback groups at Baseline (pre-test). Error bars represent SD of the mean. Task completion (TC), drill time (DT), Leeway errors (A) and Container errors (B).

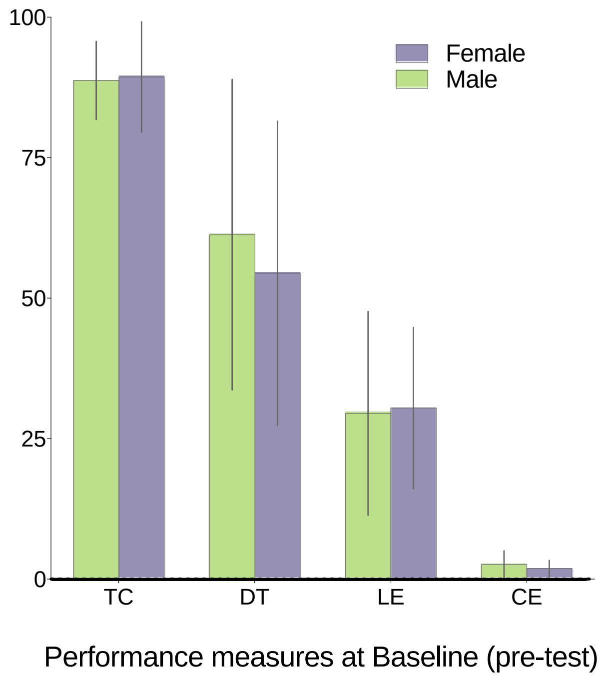

Figure 6-6 Performance measures among male and female participants at Baseline (pre-test). Error bars represent SD of the mean. Task completion (TC), drill time (DT), mean leeway errors (LE) and mean container errors (CE).

6.6.3 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 (Table 6.6-a), [*F* (2.52,151) = 1.078, $p = 0.4$, $\eta_p^2 = 0.018$]. 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, $p = 0.001$, $\eta_p^2 = 0.19$]. Post hoc analysis revealed that DFB group had significantly higher TC scores than other groups in the first ($p = 0.001$) and the fourth ($p = 0.004$) 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, $p < .001$, $\eta_p^2 = 0.24$]. Post hoc analysis revealed that IDFB group had significantly lower error scores than the other groups during first (p = .007), second (p = 0.045), and fourth (p = 0.039) training exercises.

Similarly, the leeway bottom error scores (LB) were significantly different among the groups during training, [F (2, 121.7) = 542.5, p < 0.001, η_p^2 = 0.9]. Post hoc analysis with Bonferroni corrections revealed that the IDFB group had significantly lower error scores than the other groups during first (p = 0.002), and second (p = 0.024) training exercises. The Container error (B) scores (bottom and sides) were not significantly different among the groups during training phase (χ^2 (2)< 4.2, p > 0.120).

No significant differences were found in any of the performance measures between male and female participants (t's < 1.565, p's > 0.12) at training stage.

Table 6.6-a Mean scores for the performance measures (DT, TC, errors) among the 3 experimental groups at training phase (Mean ± SEM).

	DFB	**IFB**	**IDFB**
Drill Time	53.13 ± 4.5	65.43 ± 6.2	50.04 ± 3.4
Task Completion	94.2 ± 0.71	92.58 ± 0.83	88.8 ± 1.01
Error A *(Mean Leeway errors)*	24.9 ± 2.23	22.12 ± 1.5	16.6 ± 1.27
Error B *(Mean container errors)*	1.3 ± 0.21	0.89 ± 0.08	.78 ± 0.083

6.6.4 Performance at transfer (generalisation) tests

Drill time was significantly different among groups during transfer tests, [F (2,60) = 5.75, p = 0.02, η_p^2 = 0.87]. 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 = 0.56], and error scores [F (2,60) = 2.17, p = 0.12] among the groups during the transfer tests (Figure 6-7B and Table 6.6-b).

No significant differences were found in any of the performance measures between male and female participants (t's < 1.539, p's > 0.13) at transfer stage.

Table 6.6-b Mean scores for the performance measures (DT, TC, errors) among the 3 experimental groups at transfer phase (Mean ± SEM).

	DFB	**IFB**	**IDFB**
Drill Time	69.7± 7.32	101.85± 11.6	80.7± 5.35
Task Completion	90.38± 0.78	90.34± 1.12	86.1± 0.90
Error A *(Mean Leeway errors)*	28.5± 1.80	28.28± 2.43	23.15± 1.4
Error B *(Mean container errors)*	2.7± 0.35	2.01± 0.23	1.79± 0.15

6.6.5 Performance at retention tests

During the three retention post-tests (Figure 6-7, Table 6.6-c), 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 = 0.012].

Task completion percentages were significantly different among groups during the retention tests, [F (1.8,108.5) = 614.2, p < 0.001, 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 = 0.017).

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 = 0.023], as well as during the one-month retention test, [F (2,60) = 6.5, p = 0.003]. IDFB had significantly lower LS scores than IFB (p = .019) and DFB (p = 0.004) 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 > 0.05.

No significant differences were found in any of the performance measures between male and female participants (t's < 1.384, p's > 0.17) at retention stage.

Table 6.6-c Mean scores for the performance measures (DT, TC, errors) among the 3 experimental groups at retention phase (Mean ± SEM).

	DFB	**IFB**	**IDFB**
Drill Time	61.3 ± 8.9	69.8± 7.4	57.3 ± 5.23
Task Completion	95.8 ± 0.78	95.8 ± 0.84	91.8 ± 1.38
Error A *(Mean Leeway errors)*	17.4 ± 1.9	14.9 ± 1.22	11.5 ± 1.01
Error B *(Mean container errors)*	0.44 ± 0.09	0.31 ± 0.08	.26 ± 0.05

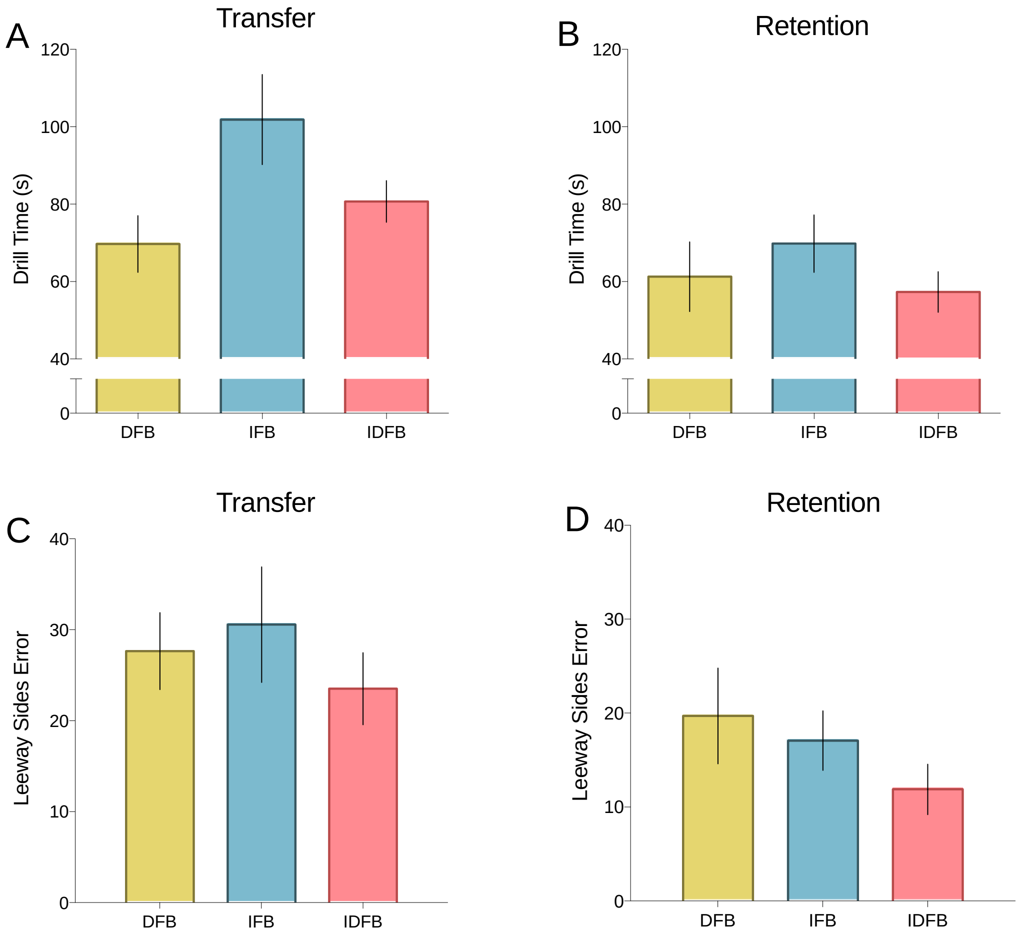

Figure 6-7 Transfer and Retention. Mean Drill time for the three groups at transfer [A] and retention tests [B]; Mean Leeway side error scores at transfer [C] and retention [D] tests. Error bars represent ±1 SEM.

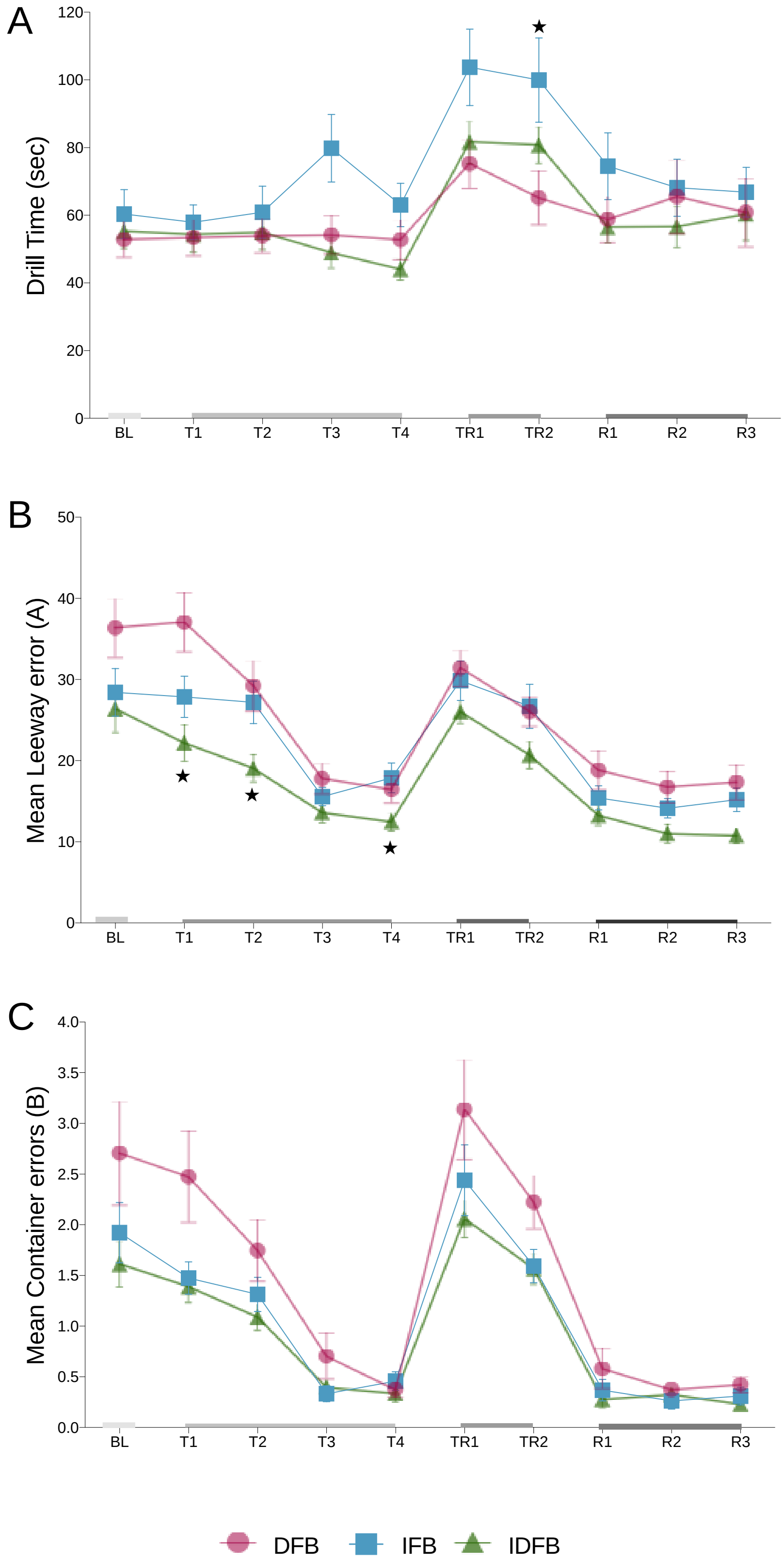

Figure 6-8 [A] Mean Drill time in seconds, [B] Mean Leeway errors A scores, and [C] Mean Container errors B scores for all 3 feedback groups across all sessions [Baseline (BL), Training (T1, T2, T3, T4), Transfer (TR1, TR2), and Retention (R1, R2, R3)]. Error bars represent SEM, and the stars indicate the statistically significant differences ($p<0.05$).

6.6.6 Performance and fine motor control abilities

The CKAT scores did not significantly differ between groups, [F (2,60) = 1.365, p = 0.263, η_p^2 = 0.044], or between male and female participants [t (61) = 1.492, p = 0.141]. 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 errors [r_s (61) = 0.128, p = 0.319].

6.7 Discussion

Novice participants were taught a basic manual dexterity task within a VR haptic simulator using qualitatively different types of feedback during training. We found 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, they 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.

Our findings are consistent with the motor learning and medical literature which indicates that multimodal feedback is more effective than unimodal feedback- particularly during the early acquisition of complex skills (Sigrist et al. 2013; Hatala et al. 2014). Whilst others have previously shown the value of providing augmented visual feedback with additional tuition sessions prior to training (Wierinck et al. 2006b), 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.

Although there were some differences among the three groups in baseline (pre-test) performance, this trend was not statistically significant (in any of the performance measures), and did not explain performance differences at subsequent experimental stages.

The device feedback group exhibited significantly higher task completion scores in less time compared to the other two groups, however, this has impacted the accuracy of performance as they also have higher error scores and subsequently lower overall performance. Since there was no time limit in any experimental phase, this trend could potentially be explained by the presentation mode of the performance measures on the computer screen, so their attention was directed toward the first information appeared on screen (which was task completion score), with little or no attention given to other measures such as error scores, because there were no guidance provided during training phase as what important measures to look for when they want to evaluate their progress. 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 (Haith & Krakauer 2013). 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 trainee 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 dental 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 (Haith & Krakauer 2013). 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 IDFB 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 (Schmidt & Wrisberg 2008) - a hallmark of MB processes.

The aim of the transfer tests is to evaluate skill learning using similar task at different training settings or different task and same training condition. The transfer phase in the present study comprises two tests, both using different tasks (abstract shapes) that were not encountered during training. This particular type of transfer is referred to as near transfer or generalization of the learned skill (Schmidt & Wrisberg 2008). Typical transfer test would be performed in different training environment (such as phantom head simulator). Our results showed that all groups exhibited lower overall performance scores at the transfer phase, particularly a sharp rise in error A and error B scores (Figure 6-8), although not statistically significant. This could be attributed to the unfamiliar features of the new shape that is not encountered during training, which is a transition from straight outline to circular and cross abstract shapes that need a slightly different preparation approach.

In the current study, the concurrent verbal feedback from the instructor is a form of knowledge of performance (KP) that did not simply indicate the presence or absence of errors, but also elaborated on how to enhance performance by directing the trainee attention to important performance aspects. Additionally, the participants were encouraged to enquire about any performance related information, therefore moving away from unidirectional instruction to dialogue-rich learning context.

In the IFB group, receiving verbal feedback alone without any visual display of performance measures from the simulator allow the student to depend solely on the verbal comments and instructions from the tutor to guide the performance. This represents a cognitive effort to understand and process what should be done until reaching a mental representation of the desired outcome before actually executing the action. This was evident in the overall trend of IFB group to spend longer time performing the task throughout the experimental phases (Figure 6-8), although this was not statistically significant except at transfer test. Additionally, the student may not be able to know what exactly contributed to good or otherwise unsuccessful performance (i.e. whether it is the leeway sides or the bottom error scores that was more serious).

On the other hand, the superior performance of IDFB group could be related to the instructor directing the trainee attention to task relevant information and specific automatic measures that are generated by the simulator, ultimately combining the important aspects of the learned task from both sources and minimizing the distraction from redundant or irrelevant information (Kalyuga 2008) which prevent cognitive overload and enhance performance. The flow of information received by the student is processed more efficiently when it is distributed over multiple sensory modalities, because of the specificity of the human senses that process various types of information differently (Sigrist et al. 2015).

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 (Chen 2001). 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. This could be further explained on the basis of what abilities constitute the main skill (see Table 2.3-a), for example in manual dexterity training, feedback is focused on how to hold the handpiece correctly, on hand-eye coordination, cutting pressure and direction etc., while training on more specific procedures such as Class II cavity preparation will require a more precise feedback about a smooth conservative preparation, retention and resistance forms and avoiding damage to the adjacent teeth etc. 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. In fact, no feedback is sometimes necessary as in the case where the students are experienced and highly motivated to monitor their own performance (Chen 2001).

The introduction of VR simulators with the real-time quantitative evaluation of the student input, add another dimension into how feedback is delivered to dental students. Based on these objective simulator-generated metrics further assessment can be provided such as objective augmented feedback to students, errors detection and correction, as well as informed decisions about student's competence in particular procedures (Porte et al. 2007).
It is critical that dental educators investigate the best pedagogical approaches to utilize such kinematic information to enrich the feedback practices during the simulation experience. They need to draw on key theoretical concepts from other disciplines (particularly education literature, motor skill learning literature) and adapt the best practices to suit our specific needs and ultimately optimize the dental student learning experience.

6.8 Conclusions

The learning of basic manual dexterity skills was accelerated when participants were provided with haptic simulator's feedback in conjunction with an experienced dental instructor feedback, 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 findings were supported by evidence from motor learning literature which describe the rapid "model-based" learning, based on previously developed 'forward models' (as seen in the combined feedback group performance), and the slower “model-free” learning based on ‘inverse models’ via trial and error (as seen in the device feedback group performance). 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. This will be discussed further in the next chapter.

Chapter 7 : Integrating Virtual Reality Haptic simulation into the curriculum - a model for preclinical dentistry

Dentistry is unique among all health care professions in two important aspects: first, dental students enter the clinical environment, coming in contact with real patients very early on in their professional careers (typically the third year of study in most dental schools around the world). The second aspect is the irreversible nature of most dental procedures (e.g. teeth preparation) that mandates the use of simulation as standard approach for the teaching of sensorimotor skills in preclinical laboratory. Phantom head simulators (bench-top or complete unit), have been the gold standard in most dental schools around the world (Fugill 2013; Perry et al. 2015). More recently, VR simulators become increasingly common in dental schools world wide, with encouraging reports of their effectiveness (Buchanan 2004; Koo et al. 2013; Vervoorn et al. 2015; Cox et al. 2015).

Despite that, it remains unclear how exactly these simulators might be integrated into existing dental curriculums, and whether they can replace and/or supplement the existing traditional simulators and how. Whilst the nature of the response to each question will vary as a function of the capabilities of each simulator model and the specific learning objective of each module, there are common themes emerging from the literature about the utility of these systems. There is also a body of theory (e.g. from cognitive psychology) and models from a number of other disciplines that have embraced the use of VR technology (e.g. the aviation, minimally invasive surgery) that could be valuable for dental education.

Furthermore, it is worth emphasising that the mere presence/ addition of haptic simulators or VR technologies does not by itself enhance learning or drive pedagogical change. It has to be thoughtfully integrated into the educational continuum and tied to specific learning objectives, so it can be utilized to its full potential (Scott 2015; Motola et al. 2013; Issenberg et al. 2005; Plasschaert et al. 2007).

Moreover, simulation as an educational methodology can be supplemented with other adjunctive pedagogical approaches (Motola et al. 2013) and flexible learning strategies at every stage of the training (e.g. Open Educational Resources (OER), e-learning, and mobile learning) to maximize the learning outcome and introduce the student to a positive multifaceted educational experience. These adjunctive strategies, also known as blended learning approaches (UNESCO-IBE 2013), if carefully selected, and strategically used, have the potential to improve the quality of teaching and learning, and enhance the students' engagement in the learning process (Garrison & Kanuka 2004).

Despite that each dental school is considered unique in its approaches and learning environment, however, the common feature that characterise almost all institutions is the intensive dental curriculum. This represents an attempt to accommodate two important constituents of dental education : basic biomedical sciences and dental sciences with associated sensorimotor learning and practical training (Hendricson & Cohen 2001). If new pedagogical innovations such as haptic VR simulators are to be efficiently implemented in such curricula, it must not be perceived as 'add on' or extra components. It should be thoughtfully integrated into the fabric of the dental curriculum using pedagogically-informed strategies.

An overview of curriculum design and models is presented in the following section.

7.1 Curriculum models

Curriculum refers to the planned sequence of intended experiences and focused instruction in a defined context with a set of goals and values that collectively describe the learner's educational experience (Knight 2001; Wiles 2008). Curriculum models are comprehensive theoretical frameworks that are utilised for the design and consolidation of various components of the curriculum based on particular principles and standards (UNESCO-IBE 2013). Several curriculum models have been described in the literature, and can be generally grouped into product models and process models. Product models focus on the outcome of the learning experience, the plans and intentions to reach the learner's destination, mostly in a teacher-led approach. The process models, on the other hand, focus on the learning process, the activities involved, and are concerned with the learner's personal and professional development, as in the learner-centred approach (O'Neill 2015; Bates 2015; UNESCO-IBE 2013). Most of the time, elements from both models (with variable emphases) are incorporated into the design of curricula and programmes, and no single best model has yet been identified that is appropriate for all contexts (O'Neill 2015).

The current proposed model is inspired by Bruner's spiral curriculum design principles (Bruner 1966), which in essence emphasise the staged logical progression from simple to complex levels, where the knowledge is consolidated and revisited at increased levels of intensity and complexity as the learners progress further in the curriculum. This design is based on and correlated with the constructivists approach to learning as pioneered by Jean Piaget (Bates 2015), that is building new knowledge on the basis of an existing knowledge and experiences. This theoretical paradigm is operationalized through simulation-based education where the students can link prior relevant experiences and knowledge to new experiences in an increasingly complex context that facilitates its application in real-world settings (Pasquale 2013).

Here, combining existing theory and evidence, a model is conceptualised that can be incorporated into an undergraduate dental curriculum (according to the learning objectives for different training scenarios) with a specific application for operative dentistry and manual dexterity training (Figure 7-1).

7.2 Rational

This model aims not only to integrate VR simulation but also to restructure the traditional dental curriculum to incorporate wider pedagogical concepts that have the potential to better prepare the student for clinical practice through deep learning strategies that goes beyond practical aspects of the profession. The valuable recommendations proposed by the ADEE (Association for Dental Education in Europe) for curriculum structure, performance assessment, learning, and teaching (Plasschaert et al. 2007; Manogue et al. 2011) have also been taken into account during the conceptualisation of the model.

7.3 Theoretical foundation of the model

The theoretical foundation of the model is derived from the following key concepts, taking into account the learning outcomes/objectives and the performance assessment needed at each dental training stage:

7.3.1 Cognitive Apprenticeship

The Cognitive Apprenticeship theory (Collins et al. 1989) is directly relevant to motor skill teaching and learning in preclinical dentistry. This theory presents six stages for teaching practical skills (modelling, coaching, scaffolding, articulation, reflection, and exploration/transfer). The first three stages have been readily applied in dental education for a number of years and are likely to be familiar to most educators, as they represent part of the classical/traditional apprenticeship model. Modelling involves demonstration of the new skill/task by the expert (dental educator) while the students observe and conceptualize the process for executing that task. In the next step the students practice that skill under the guidance of the educator (coaching) who offers guidance, advice and feedback. Scaffolding is evident in the support provided by the educator to the students while performing the task. This support should gradually decrease (fading) as the student become more capable of independent performance.

The final three stages (articulation, reflection, and exploration) focus on the learner’s own experience and observation as a route for deep learning. In articulation, the student applies the learned skill in a meaningful context and integrates the knowledge and practical experience in a problem-solving scenario. In the stage of (reflection) the learner attempts to think critically and make sense of the event, reflect on the performed actions, how they have been performed, what went well and what should be changed in the future to attain the desired outcome. Finally, in the stage of (exploration) the student is allowed to apply the knowledge and skills in different contexts (transfer) and enhance their abilities to deal with problems that might arise and has not been encountered before.

The Cognitive Apprenticeship Instructional model can be viewed as staged transition in the learning process from being externally directed by the tutor until it becomes increasingly self-directed by the learner (Whipp et al. 2000). The model highlights the importance of making the tacit knowledge of the expert more visible and explicit to the learner/novice to facilitate their conceptual modelling of the target skill. Likewise, it facilitates the learner thinking to be visible to the instructor/expert for guidance and support. This strategy is the primary difference between cognitive apprenticeship and traditional apprenticeship model (Collins et al. 1991). The cognitive apprenticeship instructional model has been applied in several health professional education settings particularly for sensorimotor skill learning (Woolley & Jarvis 2007; Lim-Dunham et al. 2016; Stalmeijer et al. 2009; Stalmeijer et al. 2013; Kilistoff et al. 2013; Ong et al. 2015).

7.3.2 Experiential learning theory

Simulation-based education in preclinical dentistry is an ideal experiential learning platform, that is mainly delivered as small group teaching in the preclinical laboratory. Experiential learning (Kolb 1984) is more than just learning through experience, it also entails thinking and conceptualizing the performed actions and planning future behaviours. Kolb’s experiential learning cycle involves 4 main stages: concrete experience, reflective observation, abstract conceptualization, and active experimentation. The effective implementation of these stages help to structure the simulation session and allow the practice/experience to be supported subsequently by reflection and analysis (Fanning & Gaba 2007), facilitating a deeper learning approach to the intended objective. Additionally, it will contribute to standardization of the simulation session among instructors with varied experiences and teaching approaches.

7.3.3 Reflection

The ability of an individual to self-reflect on his/her own actions has been identified by Schön (Schön 1984) as central to improvement and effective professional practice . He specifies two types of reflective practice based on their timing; either during the event which is described as reflection-in-action, or after the event which is described as reflection-on-action (Phrampus & O'Donnell 2013).

The metacognition concept of reflection/debriefing is an important key element not only in experiential learning and simulation-based training but also for life-long learning. Reflection on experiences is also paramount to the development of competency (Ericsson 2004), it is usually achieved through formative assessment approaches that foster the metacognitive skills and reflective practices (Crawford et al. 2007). It allows the students to be active participants in their own learning, and allow the assessment of the learning process to capture important aspects beyond the recall of scientific information (Leach 2002).

However, the concept of reflection is largely underutilized in dental training and education. This could be due to many reasons, for example, the highly dynamic dental environment with critical time limit may not support deeper analysis/reflection on actions; also the dental curriculum in most dental schools is overwhelmingly crowded with many subjects concurrently, that leaves minimal or no time for reflection (Hendricson 2012). Additionally, lack of formal training in pedagogy for most dental instructors may set another barrier for implementation of reflective practices.

Reflection and reflective learning are cognitive skills that do not evolve naturally but need continuous practice (Tricio et al. 2015). It has been reported that young dental students in their early years of dental school showed lower reflective skills compared to postgraduates (Tricio et al. 2015). Such findings emphasise the importance of early and gradual introduction of the concept of reflection in the undergraduate dental curriculum to foster deep learning strategies as early as possible among students (Whipp et al. 2000).

In the current model, the concept is gradually introduced starting with simple reflection in the first two years and expand it later (years Y3 onward) to include debriefing as an integral part of context-based simulation scenarios. Simple reflection in the current model is designed to familiarize the students with the concept of reflection and foster the habit of critically analysing their own performance and 'make sense' of the simulation sessions. A simple reflection log can be incorporated into the laboratory manual and/or included in the online learning management system (LMS) of the School. Whatever the approach, the reflection log should be simple, and easy to understand and completed by the student on a regular basis. It must be supported by instructors feedback and provide a catalyst for performance improvement (Sweet et al. 2009). Additionally, peers can be an effective source of feedback that can stimulate reflection, such formative evaluation if well designed and implemented has promising pedagogical potential (Finn & Garner 2011). Recently, formative structured peer assessment and feedback on clinical performance have been reported to positively impact dental undergraduates' reflective thinking skills as well as their academic achievement (Tricio et al. 2016). Moreover, the students' reflection records can be a comprehensive source for formative assessment and tangible evidence on their progress

(Albino et al. 2008). An example of simple reflection log (adapted from Gibbs, 1988) is presented in Table 7.3-a.

Debriefing can be introduced later into the model where the skill learning becomes more context-based with clinical case scenarios. The dental educator is in the best position of carefully selecting the cases/events that can benefit from debriefing and to apply a suitable debriefing technique. It should be noted that not all simulation scenarios need debriefing; it is much dependent on the learning objectives and whether or not the debriefing will add valuable conclusions that inform future performance (Fanning & Gaba 2007).

A critical prerequisite for successful implementation of reflection/debriefing practices is the instructors' training on structured discussions and debriefing methods (Fanning & Gaba 2007; Phrampus & O'Donnell 2013) , in addition to deep understanding of best practices in providing effective feedback (Archer 2010) to their students (e.g. using feedback models) in a supportive learning environment.

Table 7.3-a A proposed example of simple reflection log/journal (adapted from Gibbs, 1988)

Reflection step	Question
1. Description	What was the exercise/project?
2. Feelings	What did you feel/think while doing the exercise?
3. Evaluation	What was good and what was not so good/difficult about the experience?
4. Analysis	What factors helped or hindered you from doing the project properly?
5. Conclusion	Summarize what you could have done differently to achieve the outcome?
6. Action plan	For the next session, sum up what you will do based on today's experience?

7.3.4 Facilitation

The educator in the current model is described as both instructor and facilitator. Facilitation and instruction are two ends of a spectrum; on one end is the traditional instruction/lecturing, where the educator is the source of information and the learners are predominantly passive listeners without actual participation. On the other hand, in facilitation the educator is co-learning with students in a continuous active dialogue, providing them with guidance and support to reach their own conclusion (Rhodes & Bellamy 1999; Fanning & Gaba 2007; Alao et al. 2010) using various facilitation methods/styles. Effective facilitation according to Rogers (Rogers 1969; Bates 2015) encompasses three main elements/attitudes:

1- Congruence (i.e. being genuine ; accepting own limitations and expressing true feelings/opinions without fear of losing rapport with student)

2- Empathy (understanding and considering the other person's viewpoint)

3- Respect (non-judgmental acceptance of others).

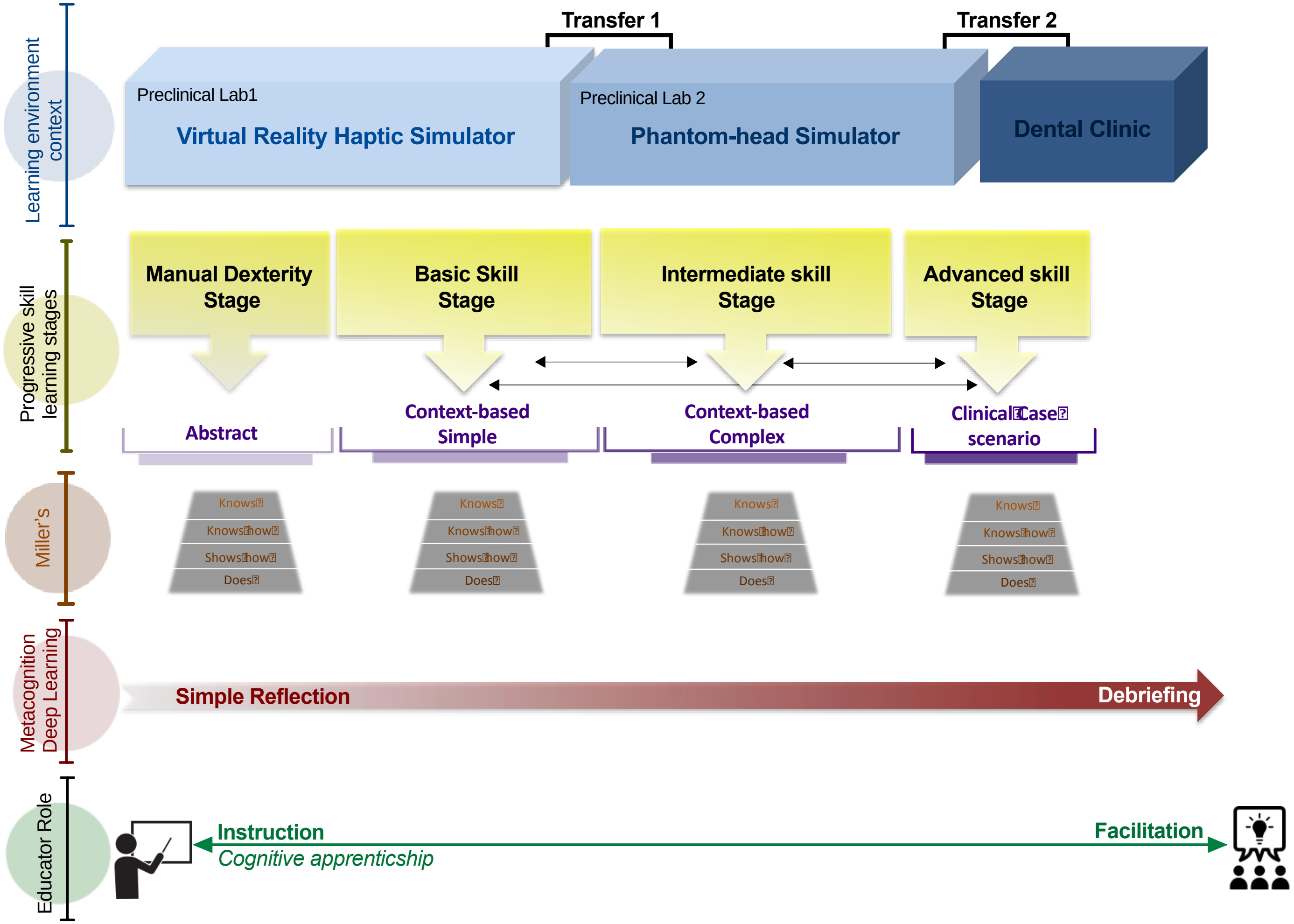

Figure 7-1 Dental skill training model

7.4 Model description

This model is suited for a five-year dentistry program, where year one and two (Y1, Y2) are preclinical, while year three (Y3) is the start of the clinical practice on real patients. The model involves four progressive dental skill-learning stages with two skill transfer stages. It is important to acknowledge that the choice of simulator type at each stage of training is very much dependent on the learning objectives of that stage, and less dependent on the simulator fidelity (McGaghie et al. 2010) .

7.4.1 Learning environment and contexts

In this model, there are three main dental learning settings: the VR haptic simulator preclinical laboratory, the phantom head simulator preclinical laboratory and the dental clinic.

A. **The first learning setting** *(the VR haptic simulator preclinical laboratory)*

It comprises two skill-learning stages: the manual dexterity and basic skill stages. The use of haptic VR simulator is based on its features that support the learning objectives of these stages, hence its early introduction. In the current model, we specifically refer to Simodont® which is designed for learning of basic motor skills necessary for dental training. The simulator's courseware has various levels of dental tasks complexities (ranging from abstract geometrical shapes to advanced treatment planning scenarios and fixed prosthodontics cases).

At these two stages the aim is to develop the fine motor abilities of the student through series of exercises starting at an abstract level and progressing into simple context-based level, with real-time objective feedback from the VR simulator on each movement, and the opportunity to repeat the training tasks as many times as required.

An example of an abstract learning is to cut/prepare a simple geometric virtual block with designated target area that has a specific depth and width. An example of simple context-based scenario is learning the basics of caries excavation in an isolated virtual tooth without details about the other teeth in the jaw, case history, or patient information. At these two stages the student will be introduced to some basic dental instruments available in the VR simulator library and their uses, such as dental handpiece with burs, dental mirror, dental explorer and hand excavators. Moreover, the student will learn basic skills such as holding the handpiece correctly, finger rest support for controlled hand movements, hand-eye finger coordination, attention to details, and using of dental mirror for indirect vision tasks.

B. The second learning setting *(the phantom head preclinical laboratory)*

The student will continue at the basic skill stage with simple contexts but will be introduced to a different learning setting, the physical phantom head laboratory. This is the first transfer stage in this model, moving from virtual environment to physical environment. The student reaches this stage with necessary basic motor skills that will be applied in new context.

After introducing the student to this new learning setting, they will start applying what has been learned in the VR laboratory into the phantom head laboratory using simulated jaws, plastic teeth and real dental instruments. An important learning objective at this stage is basic dental ergonomics (i.e. ideal seating positions of the student and the simulated patient torso), which has been made possible by the structural fidelity of the phantom head that approximate the real dental clinic setting.

Next is the intermediate skill learning stage, with complex context-based training scenarios (e.g. posterior mandibular tooth with Class II occluso-distal caries and opposing missing tooth, or anterior teeth with multiple proximal carious lesions). At this stage the student will be introduced to dental materials uses and manipulation as well as the basics of dental restorations, therefore, the training scenario will include both preparation and restoration of the carious teeth. Also at this stage the training will be expanded to include effective utilisation of various isolation techniques (e.g. rubber dam application), managing restorative cases and problem solving, as well as manipulating variety of dental equipment and instruments effectively. The third stage at this preclinical setting is the advanced skill learning stage. At this advanced stage, the training context will progress into complete clinical case scenarios with holistic approach to patient management. For example, a patient case with complete dental and medical history, dental x-rays, differential diagnosis, prognosis and proposed treatment plan.

C. **The third learning setting** (the dental clinic)

Later at the advanced skill stage, the student moves from the preclinical laboratory environment to the real-life clinical environment and this transition mark the second transfer stage in the current model. When the students reach this stage, they must be competent at the basic restorative procedures so that they need less deliberate attention in performing the skill and most of the attention should be directed toward a holistic approach for patient treatment and management. A degree of automaticity in performing basic dental tasks (e.g. controlling handpiece, mirror positioning) is needed before starting clinical treatment of patients, because it will maximize the skill transfer and help the student to concentrate on other important (but less familiar) tasks that demands higher attention (Clancy et al. 2002; Stefanidis et al. 2012).

It is important to note that the skill learning stages are progressive but there is always possibility to re-visit any of the stages depending on the learning need and objectives (shown as double-headed arrows in the model). For example, at the advanced skill stage, the student might need to learn about new tooth preparation technique, so she/he will be back at the basic skill stage to learn this particular skill.

7.4.2 Educator role

In the current model, the dual role of the educator as instructor or facilitator is much dependent on the specific learning context and could be alternating in the same stage. For example, in the early manual dexterity phase the instructor role may dominate to introduce the novices to the new learning environment and providing basic scientific knowledge, but it can also involve facilitation at specific simulation scenarios. In the more advanced skill learning stages, the facilitator role may dominate, where the educator is providing support to learners with active constructive dialogue and co-learning.

7.4.3 Assessment methods

In the model I incorporate Miller’s pyramid for clinical skills assessment/competence (Miller 1990) as a guide and a point of departure for design and implementation of suitable assessment strategies at each stage of the continuum. The assessment methods should be multidimensional covering multiple areas of competency.

At both transfer stages, the student competency can be assessed with both comprehensive summative (e.g. OSCE stations, MCQ, oral examination) and formative assessments (e.g. portfolios, reflective logbooks) as well as cumulative evaluation of student practical projects performance throughout the year.

7.5 Discussion

The model presented here is staged and progressive at several levels (learning settings, contexts, metacognition, assessment and educator role). It involves mapping different Learning settings/environment into specific learning contexts, from abstract all the way through to clinical case scenarios.

The use of Simodont at the first stage of the current model is considered a cost-effective training option particularly for early manual dexterity training, which demands unlimited repetitive practice with objective evaluation. This is possible in the phantom head laboratory but with great limitation to the number of plastic teeth that the student is allowed to use or be able to purchase, subsequently resulting in limited chances for repetitive practice due to restricted time and resources.

As the student advance into the more complex levels of skill development, the phantom head simulator becomes more suitable training option for advanced learning contexts due to its features. As noted from the model design, the phantom laboratory stage encompasses three learning contexts (basic, intermediate and advanced) and this is due to its versatility and flexibility to accommodate different levels of training scenarios effectively. Therefore, there still exists a clear need for physical simulation (phantom head) in preclinical dentistry at present, particularly for instrument handling, and manipulation of restorative material in addition to ergonomic training.

Nonetheless, with continuous technological advancement and the improvement of the Simodont's current features, the role of VR haptic simulators might not be limited to the first stage at Y1 only. Potentially it could be of utility throughout the preclinical training and beyond (i.e. in postgraduate training) for example: remedial practice for under achieving students; warm-up practice (before complex clinical cases); deliberate practice & mastery learning (Ericsson 2004; Motola et al. 2013). These suggested uses need wide scale investigation and research to prove their effectiveness in specific dental training settings.

The transfer of skill learned in the preclinical dental laboratories into clinical settings (transfer 2) is a challenging milestone, and can be explained through two levels:

1. <u>*The learning level:*</u> which includes the learned skill itself (e.g. using the handpiece, precise cutting according to specific criteria, and the use of indirect vision).
2. <u>*The performance level:*</u> which includes other factors that influence the performance of the learned skill and it is largely related to the target environment. This includes student level of stress/anxiety, the patient-student rapport, the infection control practices, the general school regulations and standards. It can be viewed as the standards that dictate the level of performance of the learned skill (Chambers 2012).

Despite every effort, the smooth transition from the preclinical laboratory to the dental clinic is a demanding process (Walls et al. 1999; Fugill 2013) that needs careful planning and combined effort from both the students and the educators. Moreover, the whole process of curriculum integration of VR simulation is complex and demanding. To be successful, it needs careful appraisal, commitment, teamwork and must go through all the integration phases (planning, implementation, evaluation, and revision) (Motola et al. 2013).

7.6 Conclusion

A pedagogical integration model is conceptualised with theoretical foundation for effective integration of Simodont® haptic dental simulator. The model takes into account the overall preclinical experience, through incorporation of wider pedagogical concepts, in the context of the simulation laboratory and the subsequent clinical setting. In addition, the model is flexible and it can be modified according to a specific module's learning objectives and/or possible advancement in the simulator's capabilities.

Chapter 8 : General discussion and Conclusion

8.1 General discussion

Before discussing the findings of the current thesis, it would be helpful to pause and reflect on the overall aims of the project. The title of this thesis (haptic-enhanced learning in preclinical operative dentistry) implies enhancement of learning of dental skills via haptics, but the concept of enhancement itself merits more clarification (Kirkwood & Price 2014) within the current context. The Oxford dictionary (Online 2010) defines enhancement as “an increase or improvement in quality, value, or extent” and enhance as “Intensify, increase, or further improve the quality, value, or extent of”. A more operational description of how technology (of various sorts) can improve learning in specific pedagogical context can be clarified using the levels described in the HEFCE revised e-Learning strategy report. The report recognizes certain possible benefits of technology on learning (HEFCE 2009) as follow:

1. Improving the efficiency of the learning process (e.g. cost-effectiveness, sustainability, time efficiency)
2. Enhancement of the existing learning process that subsequently result into improved outcome
3. Transformation of the learning process either totally, by positively changing the existing pedagogical approaches, or by introducing new approaches.

In light of this elaboration, it can be argued that virtual reality haptic simulators in their current features and capabilities contribute competently to the first two levels described above, namely, the efficiency and enhancement levels (discussed next). Nevertheless, the power to transform the existing learning process fully or partially and drive innovation is yet to be attained, potentially through future (and on-going) developments in the computational speed, haptic interface sophistication and well-designed specialised educational software.

The thematic approach presented in the current thesis enables me to discuss the findings from a broader perspective without losing the focus on the specific nature of each investigation in terms of scope, time, participants, and contexts.

The enhancement of learning brought about by the use of Simodont®, within the context of the current research, was evident on two levels, the outcome and the process. The potential enhancement of learning outcomes can be appreciated from our findings in the feedback study (chapter 6) and the prediction of future performance study (chapter 4).

In chapter 6, the incorporation of an objective real-time formative feedback during student performance did affect the efficiency of basic skills acquisition, particularly when combined with strategic support from a dental educator during the early training phase. The critical role of feedback in simulation-based education demands a careful planning of its content, timing and sources. Our findings confirmed the importance of feedback in simulation-based dental education found in the literature and went a step further by defining specifically the best approach to provide feedback in the skill acquisition phase of dental training using a virtual reality haptic simulator (i.e. the combined feedback from simulator and instructor during early skill training phase).

In chapter 4, the students' early practice on Simodont® translated into better early clinical test performance. The Simodont® is found to be highly sensitive as a basic assessment, which was able to capture some essential fine motor abilities of the student that are transferable and have been utilized in the clinical setting. Notwithstanding the relatively limited sample and the small scale of this study, the finding that successful practice on Simodont® translate into improved performance clinically, make it reasonable to suggest that more time and effort should be invested into well-planned VR training sessions early in the dental curriculum. Our finding is the first in the dental literature to report the predictive utility of haptic dental simulator for clinical performance.

On the other hand, the potential enhancement of learning process, albeit subtle, can be recognized from our stereopsis investigation findings (chapter 5) and from the proposed curriculum model (chapter 7) as an approach to learning process enhancement via pedagogically informed implementation.

Chapter 5, which investigated the role of stereopsis via two studies, shed light on human factors in virtual reality simulation – an infrequently researched area in the dental literature, despite its importance. Understanding the role of human factors in virtual reality simulators design and applications can profoundly influence its effective utility. Choosing to explore stereopsis was derived by the obvious significance of vision and depth perception in dentistry, in addition to the paucity of reported empirical evidence on this topic in the dental literature. Stereopsis is a visual quality that impacts the performance efficiency in virtual reality environment and can potentially contribute to the enhancement of the learning process by identifying the features and best practices that influence the student simulation experience. Dental educators need to realize that effective utility of virtual reality simulators demand a qualitatively different approach than that needed for the physical phantom head simulator. Moreover, the factors that influence student performance using VR simulators are different, and need to be carefully identified and addressed. Otherwise, they could potentially be missed, leading to ineffectual utilization of the simulator and less than ideal learning experience.

In chapter 7, the proposed model was an attempt to move away from an isolated view of the simulator as new pedagogical tool, to a more holistic view of the simulation experience within the broader dental education context, drawing upon theories from motor learning literature, educational psychology, and simulation-based medical education. Pedagogically informed implementation of the VR simulators into the curriculum has been identified as a key factor that will lead to effective simulation-based learning (Issenberg et al. 2005; LeBlanc et al. 2004; Plasschaert et al. 2007).

8.2 Conclusions

The findings from this thesis contribute to the growing body of literature on the utility of VR haptic dental simulators in undergraduate preclinical dental education.

Generally, haptic simulators have promising potential as pedagogical tool in undergraduate dentistry that complements the existing simulation methods.

More specifically and within the scope of the current thesis, the following can be concluded:

1. Simodont® has a good face and content validity when tested among dental postgraduate students. The participants believe that it is a valuable training tool to supplement, but not to replace, existing phantom head simulator.
2. A significant correlation was found between VR haptic simulator performance and subsequent clinical full crown test performance among a group of undergraduate dental students, with a statistically significant predictive value. Simodont® performance explained 14.2% of the variation in the clinical crown performance.
3. The performance of simulated tasks in Simodont® was optimized under stereoscopic 3D viewing condition. The presence of stereovision decreased the preparation depth-related errors but not the lateral errors. The data confirm that the participating dentists used stereopsis and its presence resulted in improved performance. These findings suggest an important role for stereopsis in dentistry and justify the design of simulators with 3D stereoscopic displays.
4. The stereo acuity values of a sample of undergraduate dental students did not significantly correlate with their performance in preclinical operative dentistry course (using VR and phantom head simulators). The complexity of dental procedures demands a more focused approach to investigate the possible effect of stereoscopic acuity particularly at task level.
5. The learning of basic manual dexterity skills was accelerated when trainees were provided with haptic device feedback in conjunction with feedback from 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 fine motor skills.

6. Combining existing theory and evidence, a pedagogical model is presented that can be incorporated into an undergraduate dental curriculum according to the learning objectives of various training scenarios, with a specific application for operative dentistry and manual dexterity training.
7. The utilization of haptic VR simulators require careful appraisal, robust validation, and pedagogically sound decisions about the best approaches that support the target learning outcomes in each context.

8.3 Limitations

There are some limitations of the current thesis that must be acknowledged:

1- The studies in the current thesis are cross-sectional in design, which is inherently limited in time and scale, and provide only a snapshot of the potential impact of the simulators on various aspects of the learning experience that limit the generalizability of the findings. A randomized controlled trial or a longitudinal study would definitely allow for more in depth investigation and more generalizable findings. However, the choice of the study design was primarily dictated by the time allotted for this PhD project (3 years).

2- The difficulty to recruit dental students to participate in a research study on undergraduate and postgraduate levels. This could possibly be attributed to their busy timetable and lack of motivation or interest. Although, I tried to improve the chances of participation (e.g. stereopsis study) by prior coordination with module leaders who were very helpful, and by clearly announcing the need for students participants via verbal, email, and poster announcements that explain the importance of the investigation in simple terms. However, since it is based on self-selection/volunteering, a very limited number of students actually participated (only 28), though I was aiming for the full cohort. Similarly, only 16 out of more than 40 postgraduate students participated.

3- There are several administrative restrictions and ethical considerations that limit the possibilities for conducting a comparative study or randomized controlled trial in this particular educational setting (undergraduate dentistry). For example, I was interested to conduct a study with first year dental students by randomly assigning them to two training groups and compare the early training on Simodont® with early training on the phantom simulator on their motor skill acquisition. However, due to some potential ethical concerns, such as the variable effect of training, even if temporary, that may benefit or hinder some students compared to others, the study was not conducted. Although, both groups would ultimately use both simulators in their preclinical training.

8.4 Recommendations for future work

Opportunities for further research in the area of haptic VR simulation in dentistry are abundant.

Based on the findings of this thesis and the detailed literature review, the following lines of research could potentially be fruitful:

1- <u>Long-term impact of haptic VR training:</u> predicated on our finding that early haptic simulator training predicted early clinical performance, it is recommended to conduct longitudinal studies and well-designed randomized controlled trials among larger cohorts of dental students to empirically evaluate the long-term impact of dental skill acquisition and performance using Simodont® or other haptic dental simulators.

2- Patient-specific simulations: future studies should explore the impact of using preoperative patient specific simulation rehearsals using Simodont® to warm-up and practice before certain clinical procedures, and determine how this approach would affect the real clinical performance on the patient.

3- Stereoacuity: is an interesting area for future work; research can be designed to explore the effect of stereoacuity on dental performance at task-level particularly among larger cohorts of dental students. In addition to longitudinally explore how the stereo deficient students will thrive in dental school, and whether they find some procedures particularly difficult to perform.

4- Deliberate practice: Simodont®**,** and other VR simulators, provide particularly unique research opportunity to explore the effect of deliberate practice (Ericsson 2004) on fine motor skill acquisition and refinement/maintenance among dental students and dentists. It is an important training framework that involves well-planned iterative practice and rigorous assessment in controlled simulation settings, yet it remains relatively unexplored concept in the dental education research.

5- Haptic rendering of restorative materials: multidisciplinary research should address the feasibility of expanding the haptic library of Simodont® to include realistic modelling of some restorative materials, which is lacking in almost all currently available haptic dental simulators, due to the difficulty of haptic rendering of the complex physical parameters of these materials. Although students must ultimately work with real restorative materials in the preclinical laboratory, however, the addition of virtual restorative materials to the VR training is assumed to be of great benefit to learn the basic principles of their handling and the detailed steps needed for their application.

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Appendices

Appendix A

A.1 Simodont® online user experience questionnaire

I. General

1) **Age** ___________
2) **Gender**
   a. Male
   b. Female
3) **Dental Specialty** __________________________________
4) **Years of dental practice (How long have you been practicing dentistry?)**
   a. 1-2 years
   b. 3-5 years
   c. 6-10 years
   d. More than 10 years

II. Simulator Realism

1) ***How realistic is the visual representation (visual realism) of the following in the Simodont :***

A. Teeth

* Very realistic __ *Realistic __*Neutral __ *Not realistic __ *Not realistic at all

B. Handpiece

* Very realistic __ *Realistic __*Neutral __ *Not realistic __ *Not realistic at all

C. Dental burs

* Very realistic __ *Realistic __*Neutral __ *Not realistic __ *Not realistic at all

D. Dental mirror

* Very realistic __ *Realistic __*Neutral __ *Not realistic __ *Not realistic at all

E. Other instruments

- Very realistic __ *Realistic __*Neutral __ *Not realistic __ *Not realistic at all

2) ***the sound of the handpiece (auditory realism)***

* Very realistic __ *Realistic __*Neutral __ *Not realistic __ *Not realistic at all

3) ***Haptic Realism***

   a. I found the Hardness, texture and tactile feedback (feeling) of enamel, sound dentin and carious dentin

* Very realistic __ *Realistic __*Neutral __ *Not realistic __ *Not realistic at all

b. ***The cutting efficiency of the handpiece, manipulation of the instruments (excavator, probe , etc)***

* Very realistic __ *Realistic __*Neutral __ *Not realistic __ *Not realistic at all

c. ***The indirect vision (mirror vision) exercise was***

* Very realistic __ *Realistic __*Neutral __ *Not realistic __ *Not realistic at all

4) ***Stereopsis Realism: the depth of the virtual scenery (the 3 D representation)***

* Very realistic __ *Realistic __*Neutral __ *Not realistic __ *Not realistic at all

III. Simulator Usability

1. ***I found the simulator unnecessarily complex***
- Strongly disagree_ Disagree_ Neither agree nor disagree_ Agree_ Strongly agree_ do not know

2. ***I thought the simulator was difficult to use***
- Strongly disagree_ Disagree_ Neither agree nor disagree_ Agree_ Strongly agree_ do not know

3. ***I think that I would need the support of a technical person to be able to use this simulator***
- Strongly disagree_ Disagree_ Neither agree nor disagree_ Agree_ Strongly agree_ do not know

4. ***I would imagine that most students would learn to use this simulator very quickly***
- Strongly disagree_ Disagree_ Neither agree nor disagree_ Agree_ Strongly agree_ do not know

5. ***I found the device very cumbersome to use***
- Strongly disagree_ Disagree_ Neither agree nor disagree_ Agree_ Strongly agree_ do not know

6. ***I felt very confident using Simodont simulator.***
- Strongly disagree_ Disagree_ Neither agree nor disagree_ Agree_ Strongly agree_ do not know

7. ***I believe that I would be a better dentist now if I had received Simodont training during my undergraduate training***
- Strongly disagree_ Disagree_ Neither agree nor disagree_ Agree_ Strongly agree_ do not know

8. **Simodont would be a useful educational tool in preclinical dental training.**
- Strongly disagree_ Disagree_ Neither agree nor disagree_ Agree_ Strongly agree_ do not know

9. **Simodont would be a useful tool in early dental skill training**
- Strongly disagree_ Disagree_ Neither agree nor disagree_ Agree_ Strongly agree_ do not know

10. **Simodont would be a useful tool in advanced dental skill training**
- Strongly disagree_ Disagree_ Neither agree nor disagree_ Agree_ Strongly agree_ do not know

11. **The indirect vision exercise in the Simodont was very useful for practicing mirror vision skills**
- Strongly disagree_ Disagree_ Neither agree nor disagree_ Agree_ Strongly

agree_ do not know

12. The indirect vision exercise experience in the Simodont approximate the phantom head exercise experience

- Strongly disagree_ Disagree_ Neither agree nor disagree_ Agree_ Strongly agree_ do not know

13. I believe that the Simodont can replace the traditional dental simulators (e.g. phantom head simulator)

- Strongly disagree_ Disagree_ Neither agree nor disagree_ Agree_ Strongly agree_ do not know

14. I believe that the Simodont can supplement traditional dental training (e.g. using phantom head simulators)

- Strongly disagree_ Disagree_ Neither agree nor disagree_ Agree_ Strongly agree_ do not know

15. Overall, my practical experience with Simodont was

- Negative_ Not satisfactory_ Satisfactory _Positive

16. I recommend the use of Simodont to new dental trainee

- Strongly disagree_ Disagree_ Neither agree nor disagree_ Agree_ Strongly agree_ do not know

IV. Further Comments

Thank you for your Time

Your participation is greatly appreciated!

A.2 Chapter 4 (Predictive validity)

A.2.1 Dichotomous distinction into high and low performance

	Low performance grade range	*High performance grade range*
VR Simodont	60 - 70.99	71 - 86
Spotter test	45 - 60	61- 80
Preclinical Crown	40 - 69	70 - 89
Clinical Crown	50 - 79.99	80 - 100

Appendix B

B.1 Information sheet (Stereopsis - section one)

UNIVERSITY OF LEEDS

Version no.1

09/11/2015

School of Dentistry
Worsley Building
Clarendon Way
Leeds
LS2 9LU
+44 (0)113 343….

Participant Information Sheet 1

Title of Study

The relation between stereopsis and dental performance *in undergraduate* students

Dear participant
We would like you to take part in the above named study, but before you decide, please read the following information.

What is the purpose of this study?
The aim of this study is:

To measure the level of stereoacuity in a cohort of dental students in their 3rd year and compare the measurements to their dental performance test results in preclinical (phantom and simodont lab) and clinical assessments.

Who is doing the study?
This study is conducted by a group of researchers in the School of Dentistry and the Institute of Psychological Sciences (Prof. Michael Manogue, Prof. Mark Mon-Williams, Dr. Faisal Mushtaq, Dr.Loulwa AlSaud).
It is part of a PhD project about the effects of haptic dental simulation on students learning by PhD student (Loulwa AlSaud) at the School of Dentistry, University of Leeds.

Why have I been asked to participate?
We are aiming to recruit undergraduate students who had been previously assessed in 3 settings: Phantom laboratory, Simodont laboratory, and operative dentistry clinic.

What will be involved if I take part in this study?
Undergraduate dental students: You will be asked to take a test to measure your 3d perception (stereopsis) using an iPad application while wearing 3d stereoscopic glasses (red-green). The test will take about 2-3minutes to complete.
The results from your practical examinations will be accessed and compared to your stereopsis test results.

What are the advantages and disadvantages of taking part?

There is no disadvantage by participation in this study. Your participation in this study will allow us to further understand how the level of stereoacuity is related to the practical dental performance. The entire study is independent of your academic studies and as such, participation is entirely voluntary.

Can I withdraw from the study at any time?

Yes. You are free to withdraw from the study at any point in time without consequences. You may stop participation during the testing period, or contact a member of the research team to request that your data be destroyed at a later date (you will be provided with contact details before the experiment). All related information will be discarded and will not be used in data analysis or in future studies.

Will the information obtained in the study be confidential?

Any information you provide that can be traced back to you will remain strictly confidential, and will be disclosed only with your permission or as required by law. If information collected in this study is published in scientific journals, where necessary, participants will be referred to by an anonymous code only. The terms of the data protection Act 1988 will be adhered to and information will be securely stored.

What will happen to the results of the study?

The results of the study will be analysed and published in a scientific peer reviewed journal.

The results of this study as well as a copy of the final paper can be provided to you upon request.

Who has reviewed this study?

This study was reviewed by DREC (Dental Research Ethics Committee), University of Leeds. (REF 230915/LA/178).

Thank you

for taking the time to read this information sheet

B.2 Information sheet (Stereopsis - section two)

UNIVERSITY OF LEEDS

Version no.1

09/11/2015

School of Dentistry
Worsley Building
Clarendon Way
Leeds
LS2 9LU
+44 (0)113 343....

Participant Information Sheet 2

Title of Study

The relation between stereopsis and dental performance in postgraduate students

Dear participant
We would like you to take part in the above named study, but before you decide, please read the following information.

What is the purpose of this study?
The aim of this study is:

To measure the level of stereoacuity (3D perception) of postgraduate dental students and compare the results to their performance on the haptic simulator Simodont.

Who is doing the study?
This study is conducted by a group of researchers in the School of Dentistry and the Institute of Psychological Sciences (Prof. Michael Manogue, Prof. Mark Mon-Williams, Dr. Faisal Mushtaq, Dr.Loulwa AlSaud).
It is part of a PhD project about the effects of haptic dental simulation on students learning by PhD student (Loulwa AlSaud) at the School of Dentistry, University of Leeds.

Why have I been asked to participate?
We are aiming to recruit dental postgraduate students and dentists with no prior experience in using Simodont, haptic dental simulator.

What will be involved if I take part in this study?
You will be asked to attend a single session (30 minutes) at the Simodont skill laboratory, School of Dentistry.

1- Practice on Simodont dental simulator (4 different exercise with different stereopsis manipulation)
2- Test stereoacuity (using iPad application: 2-3 min)
3- Answer an online questionnaire.

What are the advantages and disadvantages of taking part?

There is no disadvantage by participation in this study. Your participation in this study will allow us to further understand how the level of stereoacuity is related to the practical dental performance. The entire study is independent of your academic studies and as such, participation is entirely voluntary.

Can I withdraw from the study at any time?

Yes. You are free to withdraw from the study at any point in time without consequences. You may stop participation during the testing period, or contact a member of the research team to request that your data be destroyed at a later date (you will be provided with contact details before the experiment). All related information will be discarded and will not be used in data analysis or in future studies.

Will the information obtained in the study be confidential?

Any information you provide that can be traced back to you will remain strictly confidential, and will be disclosed only with your permission or as required by law. If information collected in this study is published in scientific journals, where necessary, participants will be referred to by an anonymous code only. The terms of the data protection Act 1988 will be adhered to and information will be securely stored.

What will happen to the results of the study?

The results of the study will be analysed and published in a scientific peer reviewed journal.

The results of this study as well as a copy of the final paper can be provided to you upon request.

Who has reviewed this study?

This study was reviewed by DREC (Dental Research Ethics Committee), University of Leeds. (REF 230915/LA/178).

Thank you

for taking the time to read this information sheet

Appendix C - (Chapter 6 – Feedback study)

C.1 Information sheet

UNIVERSITY OF LEEDS

Version no.1

12/02/2015

School of Dentistry
Worsley Building
Clarendon Way
Leeds

Participant Information Sheet

Title of Study

The effect of Haptic dental simulator's feedback on students' performance

Dear student
We would like you to take part in the above named study, but before you decide, please read the following information.

What is the purpose of this study?

Augmented feedback has an important role during training and learning of motor skills. This study explores the effect of various forms of feedback (from haptic device and instructor or from haptic feedback alone) on skill acquisition and performance during dental preclinical training.

Who is doing the study?

This study is conducted by a group of researchers in the school of dentistry and the Institute of Psychological Sciences (Prof. Michael Manogue (Supervisor), Prof. Mark Mon-Williams (Supervisior), Dr. Faisal Mushtaq, Dr.Loulwa AlSaud). It is part of a PhD project about the effects of haptic dental simulation on students learning by PhD student (Loulwa AlSaud) at the school of dentistry, University of Leeds.

Why have I been asked to participate?

We are aiming to recruit undergraduate students with no previous experience in dentistry.

What will be involved if I take part in this study?

You will be asked to attend a total of 3 days, at the Development action laboratory, School of Psychology.
Day 1 (50 min.) : fine motor skills assessment using the Clinical Kinematic Assessment tool CKAT. Afterwards, you will be asked to answer the latest version of the VARK questionnaire (version 7.8).
You will be introduced to Simodont haptic training device & to the virtual dental task to be performed. Followed by training on that task.
Day 2 (15min): one week later - task performance where you will be asked to perform a specific virtual dental task.
Day 3 (15min): one month later - task performance where you will be asked to perform a specific virtual dental task.

<u>What are The CKAT and the Simodont devices?</u>

- CKAT (Clinical Kinematic Assessment Tool) is a portable and powerful method to objectively measure detailed hand movements. In the context of this research project, the CKAT will be used for the objective assessment of your psychomotor skill prior to the start of the experiments.
- Simodont is a virtual reality haptic dental simulator. It is designed to train dental students on basic dental procedures using virtual dental instruments. Specialised software is integrated in the device, which provide wide range of dental procedures and cases with varying degrees of complexity to choose from depending on the student level.

<u>What are the advantages and disadvantages of taking part?</u>

You will receive £20 for participating time in all three sessions of this experiment. Additionally, your participation in this study will allow us to further understand the effect of haptic feedback on skill acquisition and performance.
This will help to enhance dental education research especially in the area of how best to educate dental students.
The entire study will have no bearing on your practical examination marks and the project is independent of your academic studies and as such, participation is entirely voluntary. There is no disadvantage by participation in this study.

<u>Can I withdraw from the study at any time?</u>

Yes. You are free to withdraw from the study at any point in time without consequences. You may stop participation during the testing period, or contact a member of the research team to request that your data be destroyed at a later date (you will be provided with contact details before the experiment). All related information will be discarded and will not be used in data analysis or in future studies.

<u>Will the information obtained in the study be confidential?</u>

Any information you provide that can be traced back to you will remain strictly confidential, and will be disclosed only with your permission or as required by law. If information collected in this study is published in scientific journals, where necessary, participants will be referred to by an anonymous code only. The terms of the data protection Act 1988 will be adhered to and information will be securely stored.

<u>What will happen to the results of the study?</u>

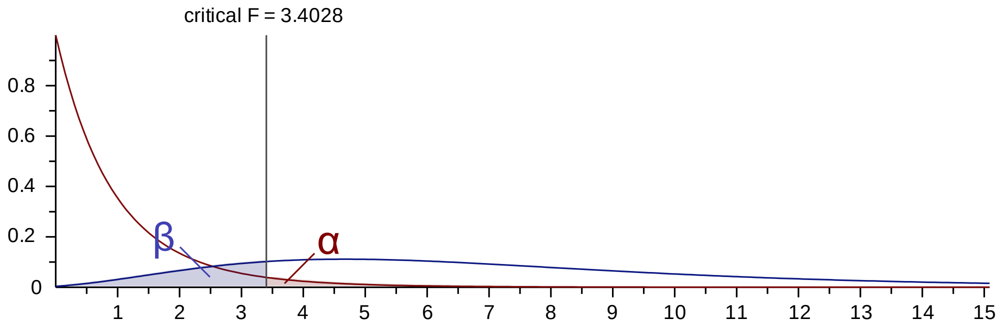
The results of the study will be analysed and published in a scientific peer reviewed journal. The results of this study as well as a copy of the final paper can be provided to you upon request.

<u>Who has reviewed this study?</u>

This study was reviewed by the School of Psychology Ethics Committee, University of Leeds. Ethical approval number **15-0039.**

Thank you
for taking the time to read this information sheet

C.2 A Priori Power Analysis



F tests - ANOVA: Repeated measures, between factors

Analysis: A priori: Compute required sample size

Input:	Effect size f	=	0.5125214
	α err prob	=	0.05
	Power (1-β err prob)	=	0.80
	Number of groups	=	3
	Number of measurements	=	4
	Corr among rep measures	=	0.5
Output:	Noncentrality parameter λ	=	11.3476976
	Critical F	=	3.4028261
	Numerator df	=	2.0000000
	Denominator df	=	24.0000000
	Total sample size	=	27
	Actual power	=	0.8149115

A statistical power analysis was performed for sample size estimation, based on data from a previous study (Wierinck et al. 2005) about the effect of augmented feedback on performance. The original sample size reported in their study was 42 reduced to 36 after dropouts, and the actual sample size became (N= 36). The effect size (ES) of the study was not reported so we calculate it (using G*Power 3.1 software (Faul et al. 2007; Erdfelder et al. 1996)) from the mean scores of each group (control, no feedback, and feedback) across test sessions. The calculated ES = 0.512 [medium effect size according to Cohen's (1988) criteria], Alpha level **α** = 0.05, and power =.80.

The projected sample size needed was calculated and is approximately N = 27, with actual power=. 8149, which means that there is 81.49% chance of correctly rejecting the null hypothesis of no difference between the 3 groups with a total of 27 participants. Thus, our proposed sample size of 63 (per group n=21) will be more than adequate for the main objective of this study and should allow for expected attrition as well as variation in our experimental design from the previous studies.

C.3 CKAT data

ID	Date	Hand	Battery score	Rescaled battery
1	20/04/15	Right	-0.42	80.42
2	13/04/15	Right	-0.35	78.03
3	28/04/15		2.14	0.21
4	30/04/15	Right	-0.69	88.60
5	15/04/15	Right	0.35	56.28
6	28/04/15	Right	0.15	62.58
7	21/04/15	Right	-0.32	77.08
8	16/04/15	Right	-0.26	75.21
9	23/04/15	Right	-0.24	74.79
10	28/04/15	Right	-0.62	86.62
11	16/04/15	Right	-0.08	69.60
12	08/05/15	Right	-0.30	76.64
13	06/05/15	Left	0.59	48.56
14	11/05/15	Right	0.15	62.43
15	15/04/15	Right	-0.28	75.76
16	17/04/15	Left	-0.35	77.94
17	21/04/15	Right	-0.23	74.23
18	30/04/15	Right	0.10	64.04
19	17/04/15	Right	-0.54	83.90
20	16/04/15	Right	-0.63	86.89
21	11/05/15	Right	0.33	56.64
22	24/04/15	Right	-0.07	69.20
23	22/04/15	Left	0.71	44.98
24	23/04/15	Right	-0.21	73.68
25	30/04/15	Left	0.38	55.12
26	11/05/15	Right	-0.91	95.49
27	08/05/15	Right	-0.36	78.33
28	08/05/15	Right	-1.05	100.00
29	24/04/15	Left	2.14	0.00
30	16/04/15	Left	-0.60	85.79
31	15/04/15	Right	-0.18	72.89
32	22/04/15	Right	0.08	64.65
33	08/05/15	Right	-0.62	86.50
34	29/04/15	Right	-0.55	84.24
35	27/04/15	Right	-0.80	92.23
36	22/04/15	Right	-0.91	95.51
37	27/04/15	Right	0.37	55.61
38	26/03/15	Right	-0.55	84.40

39	20/04/15	Right	0.08	64.67
40	20/03/15	Right	-0.48	82.01
41	27/04/15	Right	0.78	42.58
42	08/05/15	Right	1.38	23.96
43	13/04/15		-0.67	88.27
44	28/04/15	Right	1.68	14.39
45	23/04/15	Right	0.82	41.51
46	16/04/15	Right	-0.58	85.33
47	15/04/15	Right	-0.30	76.62
48	23/04/15	Right	0.72	44.66
49	20/04/15	Right	-0.24	74.75
50	08/05/15	Right	0.05	65.68
51	15/04/15	Right	-0.79	92.00
52	11/05/15	Right	0.13	62.94
53	17/04/15	Right	1.27	27.24
54	23/04/15	Right	-0.64	87.20
55	11/05/15	Right	-0.16	72.08
56	27/04/15	Right	1.60	17.01
57	15/04/15	Right	-0.36	78.55
58	23/04/15	Right	1.32	25.62
59	13/04/15	Right	0.47	52.33
60	11/05/15	Right	-0.67	87.97
61	17/04/15	Right	-0.32	77.15
62	20/04/15	Right	-0.47	81.98
63	23/04/15	Right	-0.64	78.00