# Predicting Sensorimotor and Academic Performance in Dental Students


By

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# Intellectual Properties

The candidate confirms that the work submitted is his/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 was published in February 2018. It forms the basis of Chapter 3 in this thesis. The candidate is the primary author and the named co-authors provided support through review and proofreading prior to publication.

Mirghani, I. et al., 2018. Capturing differences in dental training using a virtual reality simulator. European Journal of Dental Education, 22(1), pp.67–71. Available at: http://www.ncbi.nlm.nih.gov/pubmed/27864856

2. The paper listed below was published in March 2019. It forms the basis of Chapter 4 in this thesis. The candidate is the primary author and the named co-authors provided support through review and proofreading prior to publication.

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# Overview

High-level perceptuomotor functioning is a fundamental requirement for dental practitioners. The dental training process is a long and costly one and being able to identify individuals with the necessary aptitude for the profession is essential for the trainee and the training institutions. However, unlike academic requirements, there are relatively few measures currently used to predict an individual's aptitude for the perceptuomotor abilities necessary for a career in dentistry. In order to address this, this thesis employed the use of Virtual Reality (VR) Simulation and objective, validated measures of motor functioning to examine the utility of these tools in measuring and predicting real world dental performance. Chapter 3 investigates the ability of a VR simulation system (the Simodont) to identify differences between undergraduate dental students across year groups. The results highlighted that as students gain more experience their performance improves. Briefly, the results indicated that the Simodont has sufficient sensitivity to detect differences between novice students and well experienced students. Chapter 4 provides a formal examination of the factors considered for assessment during the Dental school's Multiple-Mini Interview (MMI) undergraduate selection process. The results indicate that two fundamental underlying traits are captured in this assessment approach- 'sensorimotor' and 'soft skills'. Chapter 5 investigates the test-retest reliability of a motor performance test deployed with dental students over a long time period. Chapter 6 examines the predictive relationship between MMI scores and performance in the degree programme through a longitudinal approach. The role of Simulation in dental education (broadly construed and as identified through an international workshop) is proposed in Appendix C. Results from this thesis reveal that the sensorimotor assessments at selection did not predict

subsequent academic performance. Unlike the sensorimotor stations, the soft skills stations were able to predict academic performance in dental students. Moreover, the Simodont and Kinematic Assessment Tool showed their potential utility in monitoring and assessing motor performance in dental students over time. And although the Multi mini interviews format still needs further refinement and development, this thesis provide a new insight into its predictive ability in predicting academic performance in undergraduate dental students.

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# List of Abbreviations

| | |
|---|---|
| **AOA** | Alpha Omega Alpha Honor Medical Society |
| **MSP** | Medical school performance |
| **USMLE®** | United States Medical Licensing Examination® |
| **NEO-PI-R form S** | Revised Neuroticism Extraversion Openness Personality Inventory, self-report form |
| **EFT** | Embedded Figure Test |
| **RMPFBT** | Revised Minnesota Paper Form Board Test |
| **IPI** | Inwald Personality Inventory |
| **SIM** | Simulator |
| **AA** | Academic Average |
| **TS** | Total Science |
| **BCP** | Biology/Chemistry/Physics grade point average |
| **HAM-Man** | Hamburg Assessment Test for Medicine-Manual Dexterity |
| **BMDS** | Basic manual dexterity score |
| **IDEA:** | Individual Dental Education Assistant |
| **KAT** | Kinematic Assessment tool |
| **MMIs** | Multiple Mini Interviews |
| **OSCE** | Objective Structured Clinical Examination |
| **ACTA** | Academisch Centrum Tandheelkunde Amsterdam |

# Chapter 1 Introduction

## 1.1 Context

Sensorimotor and cognitive abilities go hand-in-hand for successful dental practise. However, the identification of individuals for entry into dental programmes largely rests on academic requirements and very little attention is paid to the individual's aptitude for the sensorimotor abilities necessary for a career in dentistry.

The advent of virtual reality technology, allowing one to simulate the demands of dental practise, presents an opportunity to address such shortcomings. Today's simulators now include haptic technology which includes a force feedback mechanism that enables the user to interact with virtual objects through realistic feel and touch. Thus, anecdotally at least, successful performance on these tasks seems to require a combination of cognitive and sensorimotor skills. However, experimental investigations into the types of performance at the early stages of learning dentistry (and even prior to that) have been very sparse.

This thesis aims to address these issues by systematically examining the value of early assessment of skills on subsequent dental performance and the utility of a Virtual Reality haptic simulator in this process, as implemented in the School of Dentistry at the University of Leeds. Through this process, the aim is to specifically ask whether current practices allow insights into subsequent performance in dental students and whether existing admissions tools are adequate for undergraduate dental student selection.

## 1.2 Outline

To address these questions this thesis, through a combination of cross-sectional studies and one longitudinal project, focussed on three research themes; first assessing the validity of the haptic Virtual Reality simulator employed at Leeds, second, examining how sensorimotor performance in undergraduate dental students is assessed and, finally, examining the role of simulation in dental education.

The thesis is structured into seven chapters (see Figure 1-1) with four empirical chapters presented in the style of manuscripts.

**Chapter 2**: Key literature relevant to the later empirical chapters in this thesis is reviewed in this chapter. We focus on the general principles of motor skills and simulation in dentistry. This is complemented by a focused review of the literature as it relates to the empirical investigations in the following 4 chapters.

**Chapter 3** investigates the sensitivity of a haptic dental surgery simulator, the 'Simodont', to differences in dental skills training experiences.

**Chapter 4** provides a formal examination of the factors considered for assessment during the School of Dentistry's multiple mini interview undergraduate selection process.

In **Chapter 5** we investigate the changes in motor performance in dental students over time using a battery of sensorimotor tasks.

**Chapter 6** examines the predictive relationship between performance on selection interviews and performance on the degree programme through a longitudinal approach.

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Finally**, Chapter 7** provides a general discussion of the findings, explores limitations, presents opportunities for future work and concludes with a consideration of how this thesis has contributed to furthering the field of dental education research. The role of Simulation in dental education broadly construed, as identified through an international workshop is illustrated in Appendix C. This work assimilates ideas from dental educators across Europe to provide a framework for understanding the state-of-art in dental simulation.

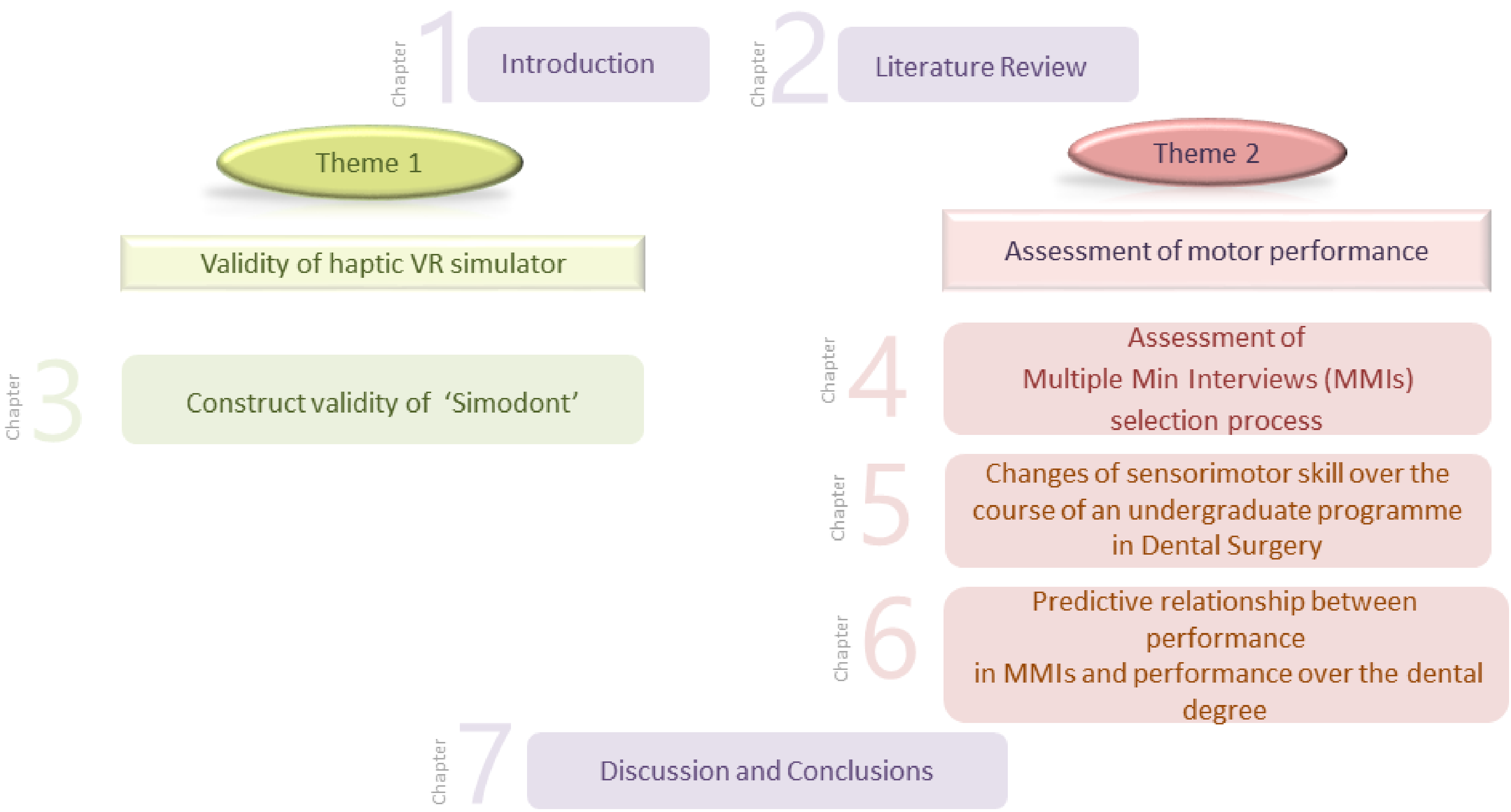


**Figure 1-1** Thesis schematic outline detailing the structure and themes of each chapter

# Chapter 2 Literature Review

The overarching goal of this thesis is to examine whether measures of a student's sensorimotor and academic aptitude are able to predict subsequent performance through dental school. As highlighted in the introduction, this goal is tackled through exploring the value of early assessment (e.g. at interview) and the utility of virtual reality simulators in this process. The overarching aim is to identify whether current practices predict real world performance and if current admission tools are sufficient for dental student selection.

In order to have a comprehensive understanding of the key concepts covered in this thesis, this chapter will explore three key concepts central to the reported research. First, we will examine the literature on sensorimotor skills in detail, then we will turn to the prediction of academic/sensorimotor performance in medical and dental education, and finally we will take a look at the contribution of simulation in this process.

The first section presents a brief introduction to the scientific literature on sensorimotor skills. We ask what are the types of motor skills necessary for dentistry? How do we learn them and what are the factors that modulate performance? We also explore the neural processes underlying skill acquisition and the coordination of skilled goal directed performance. The focus here is on highlighting the fundamental processes that are directly relevant to the motor skills that dentists must apply in the clinic for successful practise.

The second section covers current approaches to predicting undergraduate dental performance. This section illustrates the different measures (pre-admission measures such as aptitude tests or personality assessment tests) and manual dexterity tools/tests that have been used so far in the literature to predict academic/motor performance in medical and dental education and what were the outcomes of these studies.

The final section presents an overview of the concept of simulation and simulation-based education in medical/dental education. It also introduces the haptic virtual reality simulator used in the University of Leeds as it plays a key role in subsequent chapters as we interrogate its construct validity (Chapter 3), its utility in predicting dental performance (Chapter 6) and finally, lean on our experience of this simulator to inform discussions on the role of simulation in general in dental education (see Appendix C).

## 2.1 Motor skills

Motor skills are generally referred to as voluntarily actions that require movement and co-ordination of muscle and body at the same time (Haibach, Reid, & Collier, 2011).

The attainment of motor skills starts very early on in life: motor development is also often referred to as "perceptual-motor development" and/or "physical or motor coordination" in part because both the brain/nervous system and the muscles interact in intricate ways to allow an individual to move the body skilfully in manipulating objects and exploring the physical world around him/her (Bracken, 2006; Williams & Monsma, 2006).

Motor skills are broadly classified into gross and fine motor skills. Gross motor skills require the use of large muscles (e.g. crawling, running and jumping) while fine motor skills require the use of small muscles (e.g. writing or grasping using a finger and a thumb) to perform a task. Fine motor skills involve the coordination of small muscle movements—usually requiring the synchronization of hands and fingers—under control from visual information provided by the eyes (Boyle & Santelli, 1986; Spratley, 1990).

In dentistry, fine motor skills are an essential attribute of any practising dentist (Luck, Reitemeier, & Scheuch, 2000; Spratley, 1990). The acquisition of fine motor skills forms an integral part of the education of dental students (Gilad Ben-Gal, Katorza, Weiss, & Ziv, 2017; Suksudaj, Townsend, Kaidonis, Lekkas, & Winning, 2012), a process which starts as early as the selection process to gain entry to dental schools (Foley & Hijazi, 2013; Kothe, Hissbach, & Hampe, 2013, 2014).

Practising dentistry is often considered an art, requiring continued commitment by the practitioner to adopt fine motor skills to enable control of hand pieces and the delicate oral tissue in a small and contained oral cavity. The achievement and maintenance of fine motor skills in dentistry is referred to as manual dexterity or perceptual motor skills.

### 2.1.1 Neural Processes Underpinning Fine Motor Control

The areas of the brain involved in fine motor movements include the primary motor cortex, premotor cortex, presupplementary cortex and basal ganglia, supplementary cortex, posterior parietal cortex and cerebellum (Duong, Gardner, & Rucker, 2010). While these individual areas work together to fine-tune motor movements, there is a degree of functional specialisation and it is worth noting some of these key characteristics.

The primary motor cortex is involved in force generation, task-specific muscle movements and automaticity of learned movements (Duong et al., 2010). The premotor cortex is particularly important for movement planning, execution and identification of limb movements at the early stages of learning psychomotor skills (Duong et al., 2010).

During voluntary movements that are not automated the basal ganglia is stimulated and the presupplementary motor area is recruited for the learning of new sequences (Duong et al., 2010). The supplementary motor area permits self-initiation of movements, sequencing of previously memorized movements, 2-handed coordination and planning of complex movements. From the posterior parietal cortex (and the pre-motor cortex), visual feedback of limb movement is directed to the primary motor cortex.

The cerebellum is responsible for the coordination, timing and accuracy of movements (Duong et al., 2010). The degree of activation of the different areas of the brain depends on the learning stage and whether the individual is in training or has expertise (Duong et al., 2010; Watson, 2006) see Figure 2-1 below.

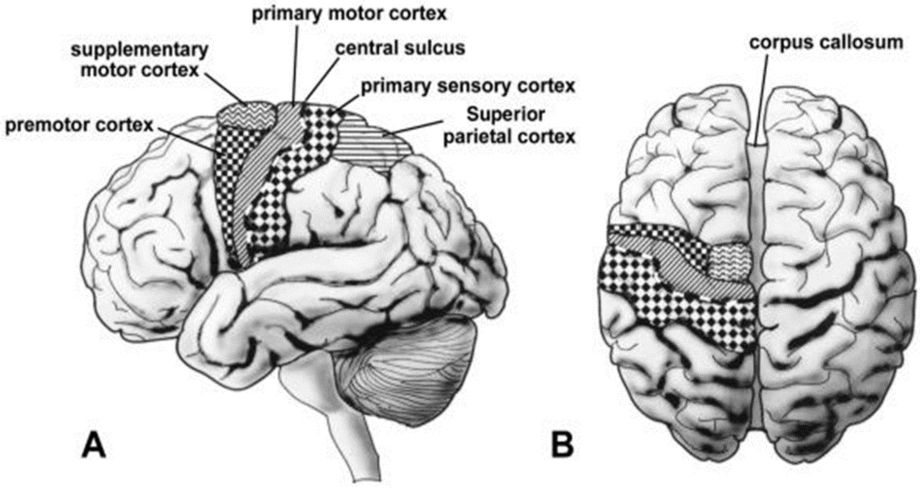


**Figure 2-1** Location of the areas of the brain involved in fine motor movements. Right hand movements are controlled by the left side of the brain, and vice versa. The corpus callosum facilitates coordination and communication between the 2 sides of the brain (Watson, 2006). This figure is reused with permission by Blackwell publishing and originally published in Watson et al 2006.

### 2.1.2 Neural Correlates of Skilled Motor Behaviour

Recent knowledge about the acquisition of fine motor skill comes from the accumulation of evidence from functional magnetic resonance imaging (fMRI) studies. Acquisition of fine motor skills in the nonexpert level depends largely on the limitations in controlling intricate finger movements. Planning of novel movements using fine motor skills requires much activity and stimulation of the central nervous system to complete a task successfully (Duong et al., 2010). These areas of the brain that requires stimulation in order to perform fine motor skills include the primary motor cortex, premotor cortex, presupplementary cortex and basal ganglia, supplementary cortex, posterior parietal cortex and cerebellum. When a fine motor sequence of hand movements are performed for the first time, two areas in the brain are activated maximally the premotor and presupplementary motor areas in order to plan extensively the attempted movements that are perceived as a new experience. Activity in the primary motor cortex is maximal only in the first 7–14 minutes then it starts to decrease (Duong et al., 2010; Karni et al., 1998; Watson, 2006). Other areas in the brain, in contrast, show less activity such as the supplementary motor cortex, the cerebellum and the basal ganglia (Duong et al., 2010; Schlaug, 2001; Watson, 2006). It has been thought that the initial increased activity in the premotor and the presupplementary motor area reflects the concentration and planning needed to activate and coordinate the different muscles specific to the task (Duong et al., 2010). Thus, planning of novel movements requires much activity and stimulation of the central nervous system.

Acquisition of fine motor skills from nonexpert to the expert level depends largely on the ability of the brain to adapt in response to a stimulus (K Anders Ericsson, Krampe, & Tesch-Romer, 1993). In well-practised professionals, movement sequences, even complex ones, have become automated; the expert employs previously established neuronal connections instead of creating new connections with each motor sequence performed as would the nonexpert (Kami et al., 1995; Schlaug, 2001; Watson, 2006) (For more details on neuronal correlates of skill learning see section 2.1.6 Hierarchical Processing of this chapter). Hence, the intensity and amount of activity stimulated in the brain of an expert are less, more highly focused and much more rapid than in a nonexpert (Duong et al., 2010).

At a neural level in well-practised professional (expert level), The centre of activity is highly focused in the primary motor cortex, and this high level of activity does not diminish over time during execution of movement sequences which in contrast to the nonexpert, activity diminishes after 7–14 minutes (Kami et al., 1995; Schlaug, 2001). For a movement that has become automated due to practice in the expert, the constant high activity level in the primary motor cortex is mainly due to the automaticity of the movements (Kami et al., 1995; Watson, 2006) .Automaticity is an important concept in skill learning and reflects the imprinting of information within the brain's circuitry (Duong et al., 2010; Karni et al., 1998; Watson, 2006). Interestingly, in well-practised professionals there is a relative absence of activity in the basal ganglia, with little activity in the premotor and presupplementary cortices and greater activity in the supplementary cortex. With regular practise, the information gets transferred from the premotor cortex and imprinted in the primary motor cortex to develop automaticity. As an indication of imprinting, an increase in finger representation has been observed within the primary motor cortex on fMRI after only 30 minutes of practice; however, this activity diminishes within 1 week in the absence of regular training. Thus, in order to develop automaticity regular training is needed to maintain the neuronal activities and connections (Kami et al., 1995).

Ericsson et al suggested that the duration for this transition from nonexpert to expert is approximately 10 years (K. A. Ericsson & Lehmann, 1996), however, the duration and frequency of practice needed within these 10 years has not been studied. Thus, in an expert, brain stimulation is less intense, more focused and rapid compared to non-expert, indicating the need for repetition and practise to facilitate imprinting of lifelong neuronal connections (Duong et al., 2010).

### 2.1.3 **Goal-Directed Actions**

Another important concept in the behavioural neuroscience of action is goal-directed behaviour, first described by Ajzen and Fishbein in the 1980s (Tresilian, 2012). For any goal-directed action or behaviour to be fulfilled it should meet a couple of objectives. The first is adaptability; this means the outcome can be attained in different conditions using different motor behaviours. The second objective is persistence in response to failure, when possible. If a particular outcome was not achieved on the first attempt, further attempts may be made until the desired outcome is reached. These principles form the basis for learning new skills and behaviours (Tresilian, 2012).

Sensory perception plays a major role in goal directed behaviour. Humans interact with their surroundings through a number of modalities including: sight, sound, taste, smell and touch. The sense of touch helps us to modify and manipulate what is happening around us (McLaughlin, Hespanha, & Sukhatme, 2002).

### 2.1.4 **Sensory Information**

The sense of touch provides information through hand movement patterns or exploratory procedures. Lederman and Klatzky et al (1987) identified these exploratory procedures and their underlying attributes e.g. lateral motion was associated with texture while pressure was used to gain information about hardness (Susan J Lederman & Klatzky, 1987) see Figure 2-2.

Reves (1931) introduced the term “haptics” which originally comes from the Greek word haptikos meaning “suitable for touch” and haptesthai meaning “able to lay hold of” (Minogue & Jones, 2006). Now, the term ‘haptics’ generally refers to the study of touch, and human interaction with the external environment through the sense of touch. This field is growing rapidly especially with the advancement of technology. Haptic devices can now provide force feedback and/or tactile feedback.

Haptic perception is a complex ability requiring adequate cutaneous and kinaesthetic information, hand-movement patterns or exploratory procedures through the sense of touch (Müürsepp, Aibast, Gapeyeva, & Pääsuke, 2012). It is produced by manual exploration of an object as a result of stimulation of the mechanoreceptors in the skin, muscle tendon and joints (Gibson, 1962). It allows us to recognise object features such as size, shape, weight, the position of certain elements within it or information about the material. One of the central characteristics of the haptic system is that it depends on the tactile perceptual field (the portion of the skin that comes in contact with the object ) e.g. obtaining information of the shape of object by using one finger or squeezing the object to get information about compliance (Gentaz, Baud-Bovy, & Luyat, 2008).

More interesting, perhaps, is the role of sensory perception and particularly haptic perception in fine motor movement in goal-directed behaviour. It is sensory perception that makes it possible for motor behaviour to be goal-directed. The only way to obtain information about whether a goal has been met or not is through sensory perception (e.g. visual feedback). Thus, sensory perception is of paramount importance to the ‘goal-directedness’ of behaviour. Therefore, goal-directed behaviour is sensorimotor in nature. Based on the above, active haptic perception involves motor procedures according to Lederman and Klatzky (S J Lederman & Klatzky, 1993; Susan J Lederman & Klatzky, 1987).Thus, haptic perception normally involves manipulation by using the hands as a perception instrument and engaging subtle activities to obtain sensory information even without looking. The schematic representation below describes the above-mentioned theory see Figure 2-2.

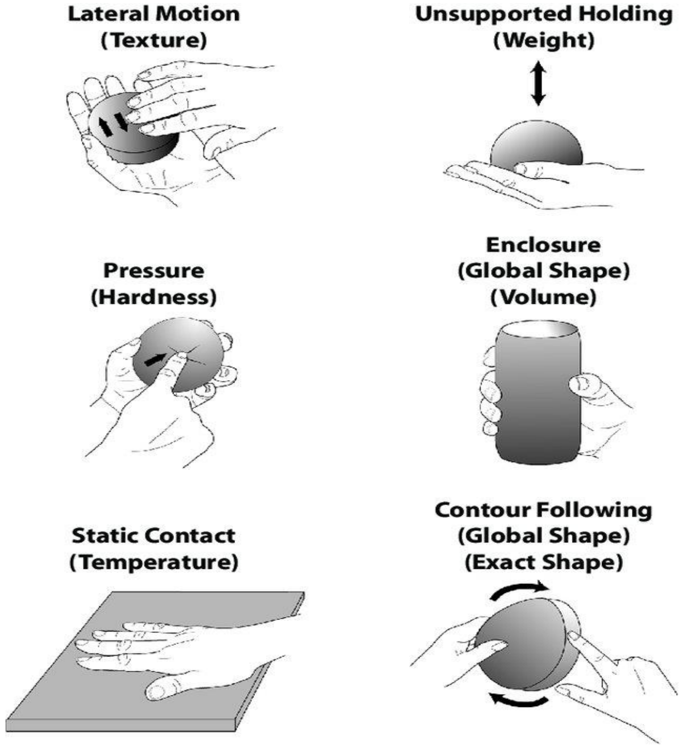


**Figure 2-2** Exploratory procedures (hand movement) for haptic perception , in order to extract information related to object properties (Susan J Lederman & Klatzky, 1987). Based on Lederman and Klatzy theory 1987.Used by permission of Springer Nature from S.J Lederman and R.L. Klatzky 2009.

The above theory is relevant to the current and future skills-based education of dental students- which requires them to develop their fine motor skills along with sensory perception in order to identify different layers of teeth through colour and textures. The importance of developing fine motor skills cannot be overstated in a complex dental environment and the need for students to learn and master intricate techniques with ever-evolving dental units in this digital era.

One of the essential aspects of this multi-faceted skills acquisition process is to ensure patient safety at all times. Hence the relevance of acquiring fundamental fine motor skills, and continuing to refine them over time. Complex modern dental practice needs delicate tissues to be managed in a small, compact oral cavity and this requires great awareness and exceptional perceptual motor skill to ensure satisfactory outcomes for both the operator and the patient.

### 2.1.5 Motor Skill Learning

What is skill learning? Motor skill learning is generally referred to as a neuronal change that leads to the accomplishment of a motor task faster, better or more accurately than before. However, for a more precise scientific definition there is little agreement in the literature. Currently, it is defined by its demarcation from other forms of learning (interestingly, most researchers can only agree on what skill learning is not!) (Diedrichsen & Kornysheva, 2015).

Skill learning falls under the broad umbrella of procedural knowledge. It is measured in terms of what we can do rather than what we can verbalise (Stanley & Krakauer, 2013). It is also important to differentiate skill learning from motor adaptation which mainly relies on the integrity of the cerebellum. Motor adaptation is defined as the act to remodify well-trained movements (such as locomotion, eye or reaching movements) to changes in the environment (Wolpert, Diedrichsen, & Flanagan, 2011). This method of learning necessitates a parametric change driven by a sensory-prediction error on a trial-by-trial basis (Diedrichsen, Verstynen, Lehman, & Ivry, 2005; Smith & Shadmehr, 2005; Tseng, Diedrichsen, Krakauer, Shadmehr, & Bastian, 2007). Unlike adaptation, skill learning includes the formation of a novel movement pattern and is featured by shifts in the speed-accuracy relationship (Reis et al., 2009; Shmuelof, Krakauer, & Mazzoni, 2012; Telgen, Parvin, & Diedrichsen, 2014).

### 2.1.6 Hierarchical Processing

One of the important features of skill learning is that it requires coordinated activity at various levels of the motor hierarchy (see Figure 2-3). This hierarchy ranges from high level movement goals (at a “selection” level) down to the specification of the actual muscle commands (an “execution” level) (Diedrichsen & Kornysheva, 2015).

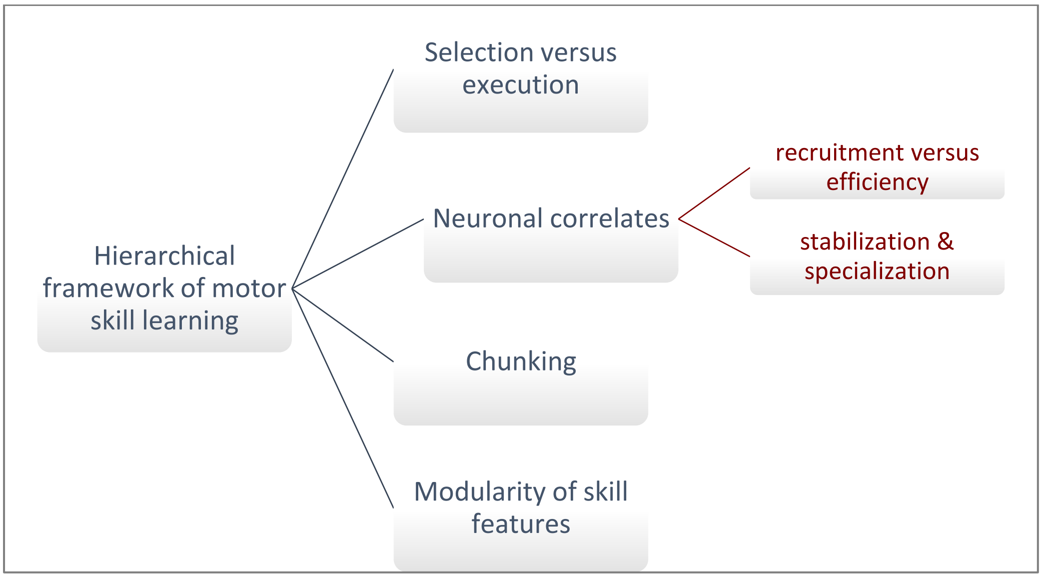


**Figure 2-3** Schematic figure illustrating the hierarchical framework of motor skill learning which reviews current behavioural and neural findings through selection versus execution, the neuronal correlates, chunking and modularity of skill features. This figure is informed by (Diedrichsen & Kornysheva, 2015).

#### 2.1.6.1 Selection versus execution

Between the levels of action selection and action execution (where the outcome of the execution level results in small muscle activity), skill learning can happen (Shmuelof et al., 2012).

Recent studies in primary motor cortex (M1) suggest that motor primitives (which are small movement elements) are encoded in the dynamics of sub-networks of neurons, which produce replicable spatio-temporal patterns of coordinated muscle activity (see Figure 2-4 A; Churchland et al., 2012; Overduin, D’avella, Carmena, & Bizzi, 2012). The selection level (Cisek, 2012) then stimulates the appropriate motor primitives in a task-specific manner (white broken lines).

This process is time-consuming as it needs to settle on the most appropriate set of motor primitives after considering multiple alternatives. Skill learning tasks involve learning at different levels. Some may start initially at the selection level while others involve learning at the execution level (Shmuelof et al., 2012). However, a lot of skill-learning tasks involve learning both at the selection and the execution level, with learning possibly progressing gradually to a more motor-oriented representation (Hikosaka, Nakamura, Sakai, & Nakahara, 2002) see Figure 2-4 (B).

The formation of skill representations reduces the load at the selection level, as less motor planning or preparation time by the learner should be able to produce movements. Shifts in time–accuracy trade-offs are one of the hallmarks of skill learning (Reis et al., 2009; Shmuelof et al., 2012).

While skill improvements can occur through the formation of a new motor primitive at the execution level, there other studies that show that such representations are formed in a hierarchical fashion, with encoding also occurring at an intermediate level between selection and execution (purple, Figure 2-4 (B).

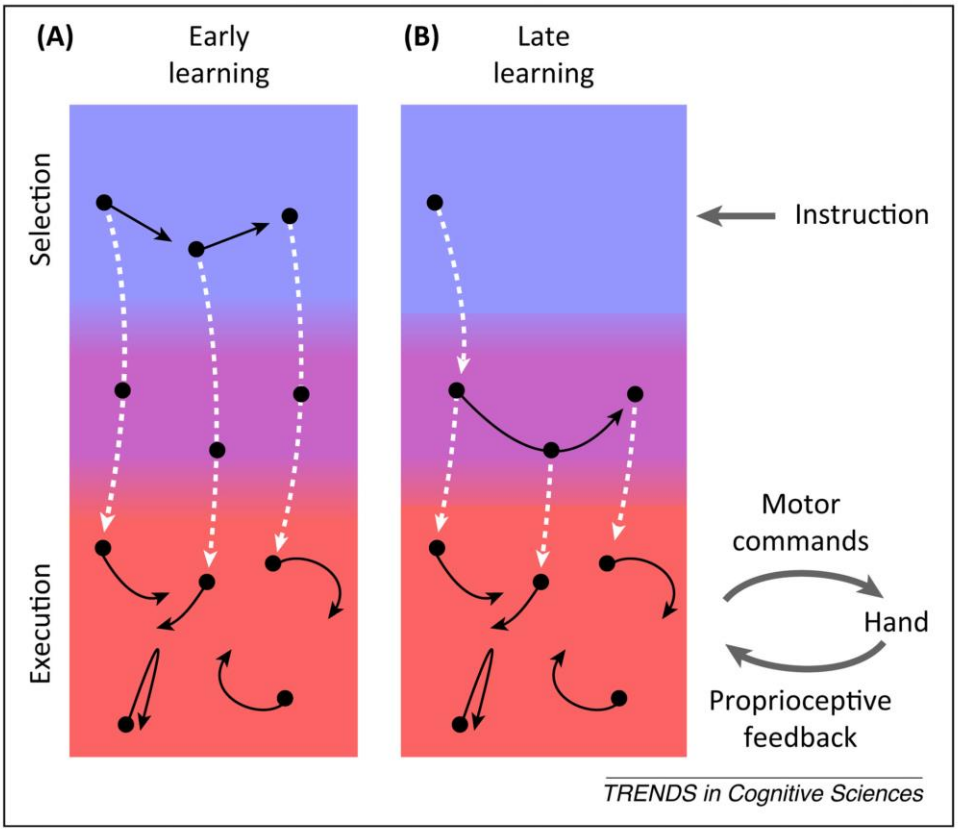


**Figure 2-4** Levels of skill learning. (A) Early in learning, the appropriate primitives are activated (white broken lines) from the selection level (blue), and this involves explicit processing of task instruction. (B) Skill learning may involve the formation of association between the selected elements at an intermediate level (purple), which enables easier recall and production of complex sequences or movement combinations (Diedrichsen & Kornysheva, 2015). Used by permission of Elsevier from Dierdrichsen and Kornysheva et al (2015).

#### 2.1.6.2 Neuronal correlates of Skill Learning: recruitment versus efficiency

What are the neural correlates of skill learning? Learning leads to neuronal recruitment meaning neurons not previously stimulated by the task becomes involved. However, studies show that after prolonged training activity decreases with learning (Jenkins, Brooks, Nixon, Frackowiak, & Passingham, 1994; Ma et al., 2010; Toni, Krams, Turner, & Passingham, 1998; Ungerleider, Doyon, & Karni, 2002; Wymbs & Grafton, 2015). Often these signal decreases are explained as a sign the region has stopped to play a part in the production of the movement, and that the skill is now represented elsewhere (Laforce &

Doyon, 2001), or that the region remains to perform the same role but does so using less pre-synaptic activity – meaning it has augmented its efficiency (Poldrack, 2015). However, there is evidence for both increases or decreases in motor and premotor areas depending on the phase of learning. The early phase of learning is often associated with an increase in overall activity, followed by reduction in later phases (Costa, Cohen, & Nicolelis, 2004). This has led to the idea that skill learning develops in discrete stages with different learning rules and plasticity mechanisms (Dayan & Cohen, 2011; Karni et al., 1998).

#### 2.1.6.3 Neural correlates of skill learning: stabilization and specialization

A different idea in the exploration for neural correlates of skill learning is that training leads to the stabilisation of the underlying neural network (Costa, 2011). In several different systems reductions in neural variability during the production of the skill with learning has been observed (Costa et al., 2004; Ganguly & Carmena, 2009; Hahnloser, Kozhevnikov, & Fee, 2002; Komiyama et al., 2010). This reduction can be taken as a mark for the emergence of a new, specialised skill representation that can stably reproduce the same spatio-temporal output (Diedrichsen, Wiestler, & Krakauer, 2013; Gallivan, McLean, Flanagan, & Culham, 2013) see Figure 2-4(B).

#### 2.1.6.4 Chunking

One of the key arguments for a hierarchical representation of motor skill is motor chunking. The concept of motor chunking as proposed by Lashley in 1951 (David A Rosenbaum, Cohen, Jax, Weiss, & Van Der Wel, 2007) has come back to prominence over recent years. Chunking is the process where multiple control sequences become idiosyncratically grouped, leading to a more fluent production of a complex series of movement patterns that are retrieved faster and performed more smoothly than the recall and execution of an individual elementary movement (D A Rosenbaum, Kenny, & Derr, 1983; Sakai et al., 2003). This process of chunking can also readily be applied to producing new movement patterns in a more flexible manner (grouping chunks of movements, rather than selecting individual elements), thus leading to faster and more efficient generalisation of a motor skill.

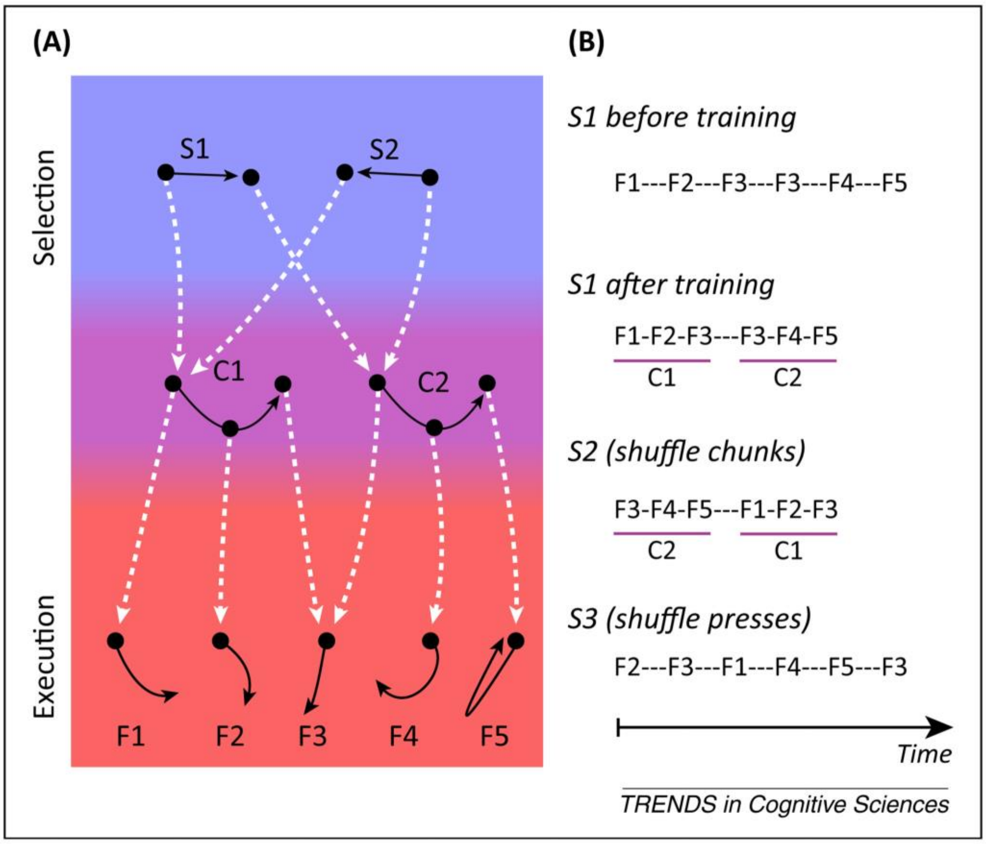


**Figure 2-5** Hierarchical representation enables movement chunking. (A) Sequence units at the selection level can trigger chunks (C1, C2) at the intermediate level (purple), which then in turn trigger individual movement elements (F1–F5). The chunk representations are efficiently shared across sequences S1 and S2. (B) Training on sequence S1 can lead to behavioral savings (faster and more accurate production) in novel sequences. Savings occur when the acquired chunks (C1 and C2) are preserved (S2), but not when they are broken up (S3) (Diedrichsen & Kornysheva, 2015). Used by permission of Elsevier from Dierdrichsen and Kornysheva et al (2015).

As shown above, the process of motor skill learning includes several stages and could start from different levels. Applying the motor hierarchy framework of motor skill learning to dental students at their early years and experienced dentists might give us better understanding of what could be the difference between both performances.

In students in their early years, the cognitive processing of task instructions occurs at the selection level. Then the most appropriate set of motor elements is mapped to task requirements in the execution level. However, in experienced dentists, the skill elements become encoded at an intermediate level within the dynamic neural network rather than in the selection level. As a result, the motor elements require little explicit or cognitive control to adapt to the new tasks (Sadnicka, Kornysheva, Rothwell, & Edwards, 2017; Sakai et al., 2003).

One of the main approaches described in research in medical education related to learning curves is to measure the number of trials required to reach competence (where performance is automated, rapid and skilled) in certain procedures (Pusic, Pecaric, & Boutis, 2011; S T Ward et al., 2017; Stephen Thomas Ward et al., 2014). In dentistry, this is particularly important as understanding the nature of the motor learning will provide proper planning of teaching as well as an insight into teaching strategies and modalities and thus help determine course length and the timing of performance measurement. Furthermore, identifying differences in learning between individuals may also have an impact on teaching and help educators in dentistry (Gilad Ben-Gal et al., 2017).

### 2.1.7 Motor Performance

Motor performance is often confused with motor learning. Motor performance is the act of executing a motor skill that results in a temporary, non-permanent change. In contrast, motor learning, is defined as a relatively permanent change in a person’s capability to perform a skill (Waras, 2016). Motor performance is a fundamental component in many health professions and in order to investigate motor performance it is essential to have a good understanding of the factors that can influence it.

Examination of the factors that impact motor performance is one of the initiatives of the National Clinical Assessment Service (NCAS) which works throughout the UK with health organisations and individual practitioners to advise on handling concerns about the performance of dentists, doctors and pharmacists (Patel et al., 2011). Identifying these factors is essential.

A previous review of factors underpinning poor performance in doctors suggested that there are several factors which have the potential to influence performance (Cox , King , Hutchinson , McAvoy, 2006). A recent dental review considered these factors and suggested a list relevant to dentistry. These factors included; demographic factors; the impact of health on performance; stress burnout and other work place related illness; smoking and the misuse of drugs and alcohol; psychological factors; the role of education and training; the impact of work-related factors; leadership in the National Health Service. The results showed that there a number of factors that have the potential to influence the performance of a dental practitioner, these include gender, ethnicity and skill-mix of the dental workforce. Other factors included health, changing working patterns, workload and the environment (Patel et al., 2011).

Other studies included factors that influence motor performance in dental students. Several significant factors have been identified including student related factors e.g. level of innate ability (P L Ackerman & Cianciolo, 2000; Phillip L. Ackerman, 1988), motivation (Kanfer & Ackerman, 1989; Yeo & Neal, 2004) and non-student related factors (Brydges, Carnahan, Backstein, &

Dubrowski, 2007; Dubrowski, Backstein, Abughaduma, Leidl, & Carnahan, 2005) e.g. learning environment. Suksudaj et al (2012) investigated if student related factors (such as innate ability and motivation) affected motor performance (Suksudaj et al., 2012). The finding showed that both innate psychomotor ability and motivation showed weak positive correlation with dental performance in a cavity preparation exercise (Suksudaj et al., 2012). Identifying these factors could help to generate an understanding of poor motor performance and what can be done to remediate this.

## 2.2 Predicting Academic Performance

To predict academic performance, it is vital to ensure that the selection methods used are robust, as selection is the first assessment for entry into medical/dental education. In the high-stakes nature of the profession and its relation to the health and wellbeing of individuals (together with societal and individual financial costs), there is also an ethical and economic responsibility for medical/dental education and training to produce competent clinicians. Thus, over the last 50 years admissions strategies have gradually moved away from subjective measures (such as personal statements and references) towards a more evidence-based models of selection (Patterson et al., 2016).

### 2.2.1 Predicting Performance in Medical Education

In the medical profession there have been numerous attempts to predict academic performance in medical education. The majority of these attempts have focused on using standardised aptitude tests. These include the Medical College Admission test (MCAT) (Callahan, Hojat, Veloski, Erdmann, & Gonnella, 2010; Dunleavy, Kroopnick, Dowd, Searcy, & Zhao, 2013), the Graduate Australian Medical School Admission Test (GAM-SAT) (Mercer, Crotty, Alldridge, Le, & Vele, 2015; Puddey & Mercer, 2014), the Undergraduate Medicine and Health Sciences Admission Test (UMAT) (D. Edwards, Friedman, & Pearce, 2013; Poole, Shulruf, Rudland, & Wilkinson, 2012), the Health Professions Aptitude Test (HPAT) (Halpenny, Cadoo, Halpenny, Burke, & Torreggiani, 2010), the UK Clinical Aptitude Test (UKCAT) (Husbands, Mathieson, Dowell, Cleland, & MacKenzie, 2014; McManus, Dewberry, Nicholson, & Dowell, 2013), the Biomedical Admission Test (BMAT) (Emery, Bell, & Vidal Rodeiro, 2011).

In addition to this, educators have relied on academic performance records (Bhatti & Anwar, 2012; Cohen-Schotanus et al., 2006; D. Edwards et al., 2013; Lumb & Vail, 2004; Luqman, 2013; Puddey & Mercer, 2014), personal statements (E. Ferguson, James, O’Hehir, Sanders, & McManus, 2003; Eamonn Ferguson, Sanders, O’Hehir, & James, 2000; Wouters, Bakker, van Wijk, Croiset, & Kusurkar, 2014), references, situation judgement tests (SJTs) (Cabrera & Nguyen, 2001; Hänsel, Klupp, Graupner, Dieter, & Koch, 2010; Lievens, 2013; Lievens, Peeters, & Schollaert, 2008; Simon, Walsh, Paterson-Brown, & Cahill, 2015), personality and emotional intelligence (EI), interviews and multiple mini interviews (Trost, Nauels and Klieme, 1998; Benbassat and Baumal, 2007; Rosenfeld *et al.*, 2008; Hofmeister, Lockyer and Crutcher, 2009; Husbands and Dowell, 2013) and employed the use of selection centres (Gafni, Moshinsky, Eisenberg, Zeigler, & Ziv, 2012; Gale et al., 2010; R Randall, Davies, Patterson, & Farrell, 2006; Ray Randall, Stewart, Farrell, & Patterson, 2006; Ziv et al., 2008).

In surgical training, predictors have included visuospatial perception (VSP) (Van Herzeele et al., 2010; Wanzel et al., 2003), psychomotor aptitude (McClusky, Ritter, Lederman, Gallagher, & Smith, 2005; Ritter, McClusky, Gallagher, Enochsson, & Smith, 2006; Van Herzeele et al., 2010; Wanzel et al., 2003), academic achievements (Brothers & Wetherholt, 2007; Goldberg, Neifeld, Wolfe, & Goldberg, 2008; Kron et al., 1985; Papp, Polk, & Richardson, 1997; Turner, Shaughnessy, Berg, Larson, & Hanssen, 2006) included Alpha Omega Alpha Honor Medical Society (AOA), Medical school performance (MSP), United States Medical Licensing Examination®(USMLE®) and research/publication experience) and video games (Miskry, Magos, & Magos, 2002; Rosenberg, Grantcharov, Bardram, & Funch-Jensen, 2003).

The predictive validity of these tests is examined in Table 2-1.

**Table 2-1** Predictors of undergraduate medical and surgical training

| **Predictors of Undergraduate medical training** | |
|---|---|
| **Predictors/Tests** | **Findings** |
| Aptitude test (e.g. MCAT, GAM-SAT, UMAT, HPAT, UKCAT, BMAT) | Mixed evidence exists among researchers on the usefulness of the aptitude tests (M. E. Kelly, Patterson, O'Flynn, Mulligan, & Murphy, 2018; Patterson et al., 2016). Some studies support the reliability and predictive validity for aptitude tests (Elam, Stratton, Scott, Wilson, & Lieber, 2002; Emery et al., 2011; Halpenny et al., 2010; Poole et al., 2012; Puddey & Mercer, 2014; Wright & Bradley, 2010) while others were sceptical of its effectiveness (Donnon, Paolucci, & Violato, 2007; Griffin, Yeomans, & Wilson, 2013; Laurence, Zajac, Lorimer, Turnbull, & Sumner, 2013; Yates & James, 2010). |
| Academic Records (e.g. A-level) | There is a high level of consensus among researchers that support the predictive validity of academic records (Bhatti & Anwar, 2012; Cohen-Schotanus et al., 2006; D. Edwards et al., 2013; Lumb & Vail, 2004; Luqman, 2013; Puddey & Mercer, 2014). One paper described a small but significant incremental validity of academic records alongside aptitude test (McManus et al., 2013). A small number of studies reported that they were not predictive of medical school performance (Al-Rukban, Munshi, |

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| | Abdulghani, & Al-Hoqail, 2010; Husbands et al., 2014; Tektas, Fiessler, Mayr, Neuhuber, & Paulsen, 2013). Although academic performance is suggested to have a high predictive power but there is concerns this power may be diminishing with increasing number of applicants having top grades and that it may be neglecting important non-academic factors required for success in medical schools (Patterson et al., 2016). |
| Personal Statements | Evidence of the predictive validity of the personal statements varied (Patterson et al., 2016). Performance on internal medicine (Peskun, Detsky, & Shandling, 2007), clinical aspects of training (E. Ferguson et al., 2003) and the number of dropouts (Urlings-Strop, Stegers-Jager, Stijnen, & Themmen, 2013) were found to be predicted by personal statements. However, a large number of researches suggested that it lacks reliability and validity (Eamonn Ferguson et al., 2000; Husbands & Dowell, 2013; Kreiter & Axelson, 2013; Oosterveld & ten Cate, 2004; Wouters et al., 2014) but still personal statements remains widely used worldwide. Some authors suggested that personal statements may have some value by helping applicants to make a more |

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| | informed decision to application through awareness of the characteristics of the medical degree (Wouters et al., 2014). |
| References | References were of limited use in predicting performance at a medical school and there is a general agreement that they are neither a reliable nor a valid tool for selecting medical students (DeZee et al., 2014; E. Ferguson et al., 2003; Patterson et al., 2016). However, it still remains a common feature of medical school selection. |
| Situational judgement tests (SJTs) | SJTs tests are usually complex to develop and there is a variety of options available in terms of item format, instructions and scoring (Patterson et al., 2016). Although there were some concerns about the impact of coaching (Cullen, Sackett, & Lievens, 2006; Lievens et al., 2008; Rostom, Watson, & Leaver, 2013) but there is general agreement among researchers that SJTs when properly constructed can form a reliable and valid selection method not only in medical students but across a range of occupations (Lievens et al. 2008; Cabrera & Nguyen 2001; Christian et al. 2010; Hänsel et al. 2010). |
| Personality and Emotional intelligence (EI) | The association between personality domains and medical school performance are often complex see below. Studies investigated the association between the big five |

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| | personality traits which includes (openness, conscientiousness, extroversion, agreeableness and neuroticism) (Haight, Chibnall, Schindler, & Slavin, 2012; Hojat, Erdmann, & Gonnella, 2013; Lievens, Coetsier, De Fruyt, & De Maeseneer, 2002). Despite some studies showed no evidence between personality trait and performance (Haight et al., 2012), a number of studies found conscientiousness to be a predictor of pre-clinical knowledge and examination results (E. Ferguson et al., 2003; Eamonn Ferguson et al., 2000; Lievens et al., 2002). On the other hand, conscientiousness was found to be a significant negative indicator of clinical performance (Eamonn Ferguson et al., 2000, 2014). Predictive validity of EI is still on its early stages. Some studies found no correlation between EI and performance of medical students (Carr, 2009; Lin, Kannappan, & Lau, 2013). However, two studies provided a tentative evidence for its use in medical students (Carrothers, Gregory, & Gallagher, 2000; J. C. Edwards, Elam, & Wagoner, 2001) and that the ability-based measure of EI the Mayor Salovery-Caraso Emotional Intelligence Test (MSCEIT) correlates with measure of success in medical schools(Brannick, Grichanik, Nazian, Wahi, & Goldin, 2013). |

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| Traditional Interviews and Multiple mini interviews (MMI's) | Traditional interviews are among the widely used tool in selection for medical school admission. Despite it being widely used there are some evidence that suggests it lacks reliability and predictive validity (Basco, Gilbert, Chessman, & Blue, 2000; Benbassat & Baumal, 2007; Trost et al., 1998). On the other hand, Structured Multiple mini interviews have been found to have adequate psychometric properties (Dore et al., 2010; Eva, Rosenfeld, Reiter, & Norman, 2004; Hofmeister, Lockyer, & Crutcher, 2008; M. Kelly et al., 2014), its construct validity remains exploratory and largely inconclusive. Evidence with regards the predictive validity of the Multiple Mini Interviews is emerging from exploration of the correlation between performance on MMI's and subsequent performance (Hofmeister et al., 2009; Hopson et al., 2014; Pau et al., 2013; Reiter, Eva, Rosenfeld, & Norman, 2007; Rosenfeld et al., 2008). |
| Selection centres | Provisional evidence suggest that selection centres may have the potential for assessing applicants' aptitude in medicine through developing assessment tools such as behavioural stations, autobiographical questionnaire, and a judgement and decision-making questionnaire. (Gafni et al., 2012; Ziv et al., 2008) and in post graduate training it is thought to have a predictive validity for performance through |

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| | creation of stations such as structured interview, portfolio review, reflective written exercise and simulation consultation).that aims to assess competency domains based on an expert consensus or a job analysis (Gale et al., 2010; R Randall et al., 2006; Ray Randall et al., 2006). |
| **Predictors of Surgical training** | |
| Visuospatial perception (VSP) | Three levels of the visuospatial perception test were used as predictors, low level (referred edge and surface extraction), intermediate level (referred to whole object recognition and mental visualisation of spatial relation of objects parts in two dimensions) and high level (referred to mental visualisation involving two and three-dimensional spatial rotations and translation) (Maan, Maan, Darzi, & Aggarwal, 2012). Two studies showed a correlation between intermediate level VSP and efficiency in performing surgical tasks (Van Herzeele et al., 2010; Wanzel et al., 2003). One study showed a correlation between high level VSP and improved efficiency but no significant correlation between low level VSP and efficiency in performing surgical tasks (Wanzel et al., 2003). |
| Psychomotor aptitude | The psychomotor aptitude included testing for fine motor dexterity (FMD), gross motor dexterity (GMD) and hand steadiness and coordination (HSD).The FMD were tested |

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| | using grooved pegboard, Crowford small parts dexterity, or finger tapping while the GMD were mainly tested using the Purdue pegboard. The HSD were tested using Gibson Spiral Maze, ADTRACK 2 a joystick-controlled game or Tremor test. A Minimally Invasive Surgical Trainer VR (MIST-VR) was used to test both FMD and GMD. One study reported GMD using Purdue pegboard predicted performance in surgical task (Van Herzeele et al., 2010). However, other studies reported no correlation between FMD using grooved pegboard and CSPD and surgical task performance (Van Herzeele et al., 2010; Wanzel et al., 2003).The MIST-VR on the other hand was able to predict the number of trials required to reach performance goal (McClusky et al., 2005; Ritter et al., 2006). |
| Academic achievement (e.g. AOA, MSP and USMLE®) | Predictors of academic achievement were tested mainly to predict Training programmes outcomes (TPO), In-training examinations (ITE), Faculty assessment, Board examinations and dexterity.<br><br>With TPO a significant positive correlation was found between AOA, MSP and success of training completion (Kron et al., 1985; Turner et al., 2006). One study reported no correlation between USMLE® and successful completion of training (Turner et al., 2006). |

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| | ITE was found to be correlating to AOA, MSP and USMLE® step 1 score (Brothers & Wetherholt, 2007; Turner et al., 2006). However, a negative correlation was found between research experience and performance on ITE (Brothers & Wetherholt, 2007).<br><br>The faculty assessment showed conflicting results AOA and research experience showed no correlation to faculty assessment (Brothers & Wetherholt, 2007; Kron et al., 1985). The MSP (Andriole, Jeffe, & Whelan, 2004; Brothers & Wetherholt, 2007) and USMLE®(Andriole et al., 2004) showed a significant correlation in some studies and no correlation in another study (Papp et al., 1997). In one study USMLE® showed a significant negative correlation with faculty assessment (Brothers & Wetherholt, 2007).<br><br>Performance in Board examination showed a significant positive correlation with AOA, MSP and USMLE®. (Brothers & Wetherholt, 2007; de Virgilio, 2010; Dougherty, Walter, Schilling, Najibi, & Herkowitz, 2010; Shellito, Osland, Helmer, & Chang, 2010; Swanson et al., 2009; Turner et al., 2006) A negative correlation was found with research experience and performance in board examinations in one study (Brothers & Wetherholt, 2007). |

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| | Dexterity reported no correlation with research experience (Salgado, Grantcharov, Papasavas, Gagne, & Caushaj, 2009) and in one study and MSP predicted reduced time to complete dexterity test (Goldberg et al., 2008). |
| Video games | A significant positive correlation was found between time to complete a surgical task and time to complete a lap in a racing video game in one study (Miskry et al., 2002). Another study found video game experience predicted a lower number of errors in surgical tasks while no correlation with the number of unnecessary movement in a surgical task (Rosenberg et al., 2003). |

### 2.2.2 Prediction of Academic/motor performance dental education

The process of undergraduate dental education in the UK is both lengthy and expensive. For the student and institutions, it is essential to identify individuals with the necessary aptitude for the profession. The selection of the best suited students at the outset will help in many ways, recognition of low performance can occur at an early stage and early support will lead to a more beneficial learning environment and boost student course performance. It will also help in reducing the number of dropouts (by identifying those who do not have the basic skills for the profession) and obtain suitable and well-motivated candidates able to excel in their studies (Polyzois, Claffey, McDonald, Hussey, & Quinn, 2011). Moreover, dentistry is a profession that requires superior hand eye coordination- a dentist is required to work with precision on an extremely small scale in order to perform dental procedure, and this is vital to ensure the integrity of the profession and patient safety (ADEA House of Delegates, 2011; Boyle & Santelli, 1986; Lugassy et al., 2018). Thus, identification of the domains that are needed for potential dentist and testing it at the selection process is crucial (ADEA House of Delegates, 2011; Cowpe, Plasschaert, Harzer, Vinkka-Puhakka, & Walmsley, 2010).For these reasons, prediction of dental performance is of great interest for educators. However, thus far, prediction of dental performance has largely centred on prior academic performance, psychological assessment-based tests, interview scores and manual dexterity measures (see Table 2-2 Examples of predictors of dental performance).

**Table 2-2 Examples of predictors of dental performance**

| Predictors of dental performance | Example | Description |
|---|---|---|
| Prior academic performance | • GPA | College grade point average is a standard way of measuring academic achievement. All grades from all current classes are averaged for the making period. |
| | • DAT | Dental Admission/Aptitude Test is a multiple-choice standard exam taken by potential dental students in US and Canada. It's a computerised based test. It has four sections:<br>• Survey of natural sciences (Biology and Chemistry).<br>• Perceptual ability test (PAT) Which includes a 3D manipulation and spatial reasoning.<br>• Reading comprehension.<br>• Quantitative reasoning. |
| Manual dexterity and perceptual ability test. | • Chalk carving, Fabrication of wax teeth, Wire bending and Cavity prep | Cavity prep: Cavity preparation |
| Personality assessment | • MBTI | Meyers-Briggs Type Indicator is a psychometric questionnaire designed to measure psychological preference in how people perceive the world and make decision. |
| | • MMPI | Minesto Multiphasic Personality Inventory is a psychometric test of adult personality and psychopathology. |
| | • CPI | California Personality Inventory: is a self-report inventory which was created to assess the everyday "folks-concept" that ordinary people use to describe the behaviour of the people around them. |

Prior academic performance includes the United Kingdom's Clinical Aptitude test (UKCAT) which was the aptitude test taken to apply for most of the dental and medical schools in the UK, but it has now been replaced by Biomedical Admissions Test (BMAT). The main goal of having the UKCAT was to widen university participation from lower socioeconomic groups and ethnic minorities and to help choose the best future health professionals. Previous research on UKCAT was performed on early years and later years of medical schools and the results were found to be equivocal.

In the early years, one study demonstrated that UKCAT could not predict performance in year 1 medical students but it is thought that its subtests maybe of value, as an association was found between the decision making analysis with re-sits of examinations in medical schools (Lynch, MacKenzie, Dowell, Cleland, & Prescott, 2009; Yates & James, 2010). One study found a predictive ability between UKCAT and exam performance in years 1 and year 2 (Wright & Bradley, 2010), but others found poor predictive value between UKCAT and year 1 (McManus et al., 2013) or during the first 2 years of medical school (Yates & James, 2010).

In later years of medical school, one study found that UKCAT predicted performance of medical students in later years (Husbands, Mathieson, Dowell, Cleland, & MacKenzie, 2014; Lynch et al., 2009), but Yates and James (2013) found no parts of the UKCAT proved to be an independent predictor of clinical course marks (Yates & James, 2013). In dentistry, one study found the UKCAT could not predict dental exam performance during the first year of the programme. However, it predicted the likelihood of the candidate being offered a place (Lala, Wood, & Baker, 2013). These results questioned the use of UKCAT as a sole method in the dental and medical applicant selection process

(Lala et al., 2013). Another study linked poor UKCAT score to poor academic performance (McAndrew, Ellis, & Valentine, 2017).

Other prior academic performances include high school grade point average (GPA), the GPA is the average value of the accumulated final grades obtained by the student in various courses over time. It reflects the academic achievement level of the student and their scholastic abilities. Another test is the dental admission/aptitude tests (DAT), which are commonly used in US and Canada. The DAT is a multiple-choice test that has been in operation since the 1950's. The DAT compromises four sections: survey of the natural sciences which consist of questions in biology, general chemistry and organic chemistry and a perceptual ability test, which examines 'perceptual abilities' (specifically areas of 3 dimensional manipulation and spatial reasoning), Reading comprehension and Quantitative reasoning which test basic mathematical skills and critical thinking (Ada, 2017). Extensive studies have been reviewed to determine the effectiveness of these tests.

Some studies have shown that the DAT and GPA were able to predict performance while others had a negative result. (Wood, 1979; Sandow *et al.*, 2002; Bergman *et al.*, 2006; Beier *et al.*, 2010; Allareddy, Howell and Karimbux, 2012; Carroll and Schuster, 2015). However, a recent review concluded that pre-admission GPA is the best predictors of academic success (Salvatori, 2001) but it is worth noting that in order to excel in a health profession non-cognitive traits such as communication, ethics and ability to show empathy are essential and needs to be tested (ADEA House of Delegates, 2011; Cowpe et al., 2010). These are typically not tested in these pre-admission measures. These tests also fail to assess candidates' personal attributes or potential clinical ability.

Some papers looked into the factors that help success in the health profession, and these studies found that academic abilities are not the only factors which are deemed essential for the health profession. Factors such as general intelligence, positive attitude, noncognitive skills, spatial ability and manual ability all are necessary for a health professional (Heintze, Radeborg, Bengtsson, & Stenlåås, 2004; Powis, 2015; Schmidt & Hunter, 1998).

Psychological assessment tests used to predict dental ability include NEO-PI-R: Form S (Revised Neuroticism Extraversion Openness Personality Inventory, self-report form) to test personality, Embedded Figure Test (EFT) to test Field dependence-independence, Revised Minnesota Paper Form Board Test (RMPFBT) and Dimension and block test of the IPI (Inwald Personality Inventory) Job Test to test spatial ability. NEO-PI-R: Form S was used to measure 5 personality domains (neuroticism, extroversion, openness, agreeableness, conscientiousness) and six facets of each domain. The Embedded Figure Test (EFT) is a ‘visual perception’ test that measures an individual’s ability in ‘disembedding’. This is an individually administered test that requires the subject to find simple geometrical figures that are embedded in more complex geometrical fields (Evans & Dirks, 2001). These tests have shown varying results; some have showed strong prediction in preclinical and clinical performance (Evans & Dirks, 2001; Suddick, Yancey, Devine, & Wilson, 1982) , however, other studies found no correlation (M. K. Chen, Podshadley, & Shrock, 1967; Westerman, Grandy, Combs, & Turner, 1989; Wilson, Suddick, Shay, & Hustmyer, 1981).

Interview scores, which are based on first impressions and gaining information from the interviewees such as motivation, learning styles, knowledge of the profession, communication skills, decision making, academic competency and sense of responsibility (Al-Nasir & Robertson, 2001; Evans & Dirks, 2001; Sandow et al., 2002) have a high face validity and acceptable interrater reliability. However, they have been identified as being amongst the most subjective and variable measures with studies showing high variability in content validity and susceptibility to bias (Cleland, Dowell, McLachlan, Nicholson, & Patterson, 2012).

Manual dexterity tests (MDT) have been conducted in order to assess these psychomotor skills using different instruments see Table 2-3 such as O-Conner tweezer (Lundergan, Soderstrom, & Chambers, 2007; Waldman, Macdonald, & Wilson, 1995), paper and pencil (Coy, McDougall, & Sneed, 2003; Freeberg, 1966), chalk carving (Gansky et al., 2004; Peterson, 1974), plastic typodont (Polyzois et al., 2011), wire bending test (Kao, Ngan, Wilson, & Kunovich, 1990; Kothe et al., 2014), basic manual dexterity tests (Giuliani et al., 2007) and Crawford Small Parts Dexterity test (Boyle & Santelli, 1986). These manual dexterity tests mainly assess manual dexterity abilities. However, most of these tests found no correlation with preclinical success (Gansky et al., 2004; Luck et al., 2000; Oudshoorn, 2003; Polyzois et al., 2011). Haptic virtual reality systems have promise but are still at an early stage (Mirghani et al., 2018)

Furthermore, there are a wide range of outcome measures used as indicators of student performance in dental schools such as the National Board of Dental Examination (NBDE) part 1 and 2 scores in the United States; performance in a problem based learning approach (PBL) curriculum; grades obtained in clinical course; clinical productivity and performance; scores in license exams; and dental school GPA. Although these approaches have been interesting, unfortunately most of the results have often been either inconclusive or conflicting (Kirby, 1979; Suddick *et al.*, 1982; Raybould, Raggard and Norton, 1983; Walcott, Knight and Charlick, 1986; Kramer, 1986; Luck, Reitemeier and Scheuch, 2000; Al-Nasir and Robertson, 2001; Gray, Deem and Straja, 2002; Gansky *et al.*, 2004; Giuliani *et al.*, 2007; Allareddy, Howell and Karimbux, 2012; Carroll and Schuster, 2015).

All of the tests reported above have aimed to test a specific domain of competency (the ability of a dental practitioner to start independent unsupervised dental practice, the term competence involves knowledge, ethical values, professionalism, critical thinking, experience, problem solving skills and technical and procedural skills (ADEA House of Delegates, 2011)) required for a potential dental student to become a competent dental practitioner. In fact, for beginning general dentists there are more domains of competency that are deemed necessary. According to the American Dental Education Association (ADEA) the domain of competencies for the entry-level of general dentist include critical thinking, professionalism, communication and interpersonal skills, health promotion, practice management, informatics and patient care (ADEA House of Delegates, 2011). Cowpe et al (2009) identified seven domains in Profile and Competence for the graduate European dentist. These included: Professionalism; Interpersonal; communication and social skills; Knowledge Base, Information and Information Literacy; Clinical Information Gathering; Diagnosis and treatment planning; Therapy: Establishing and Maintaining Oral Health; Prevention and Health Promotion (Cowpe et al., 2010). Therefore, what we need is an assessment that covers most of the core skills that are required for potential dental students at the entry level (to help them deliver appropriate oral care, consistent with patient wellbeing) and also able to predict future performance. Although those domains of competency are very useful in providing dental teaching institutions with a benchmark that can enhance their curriculum, evaluate students and assess the effectiveness of their undergraduate programme (Cowpe et al., 2010) but may also aid in the selection process of potential dental students. Identifying those fundamental competencies will allow us to identify those students who can acquire rapidly the skills which are needed throughout the undergraduate programme and thus provide those potential students with a good start and a smooth learning journey. For this purpose, now teaching dental institutes are shifting from traditional interviews to Multiple Mini-Interviews (MMIs) as a new tool for selection. MMIs assess several domains of competency required for beginning dentists (unlike traditional interviews). Recently, several studies on admission criteria concluded that two or more admission criteria were more reliable in predicting dental performance (Sandow et al., 2002). Thus, it is important that each element of the interview should be valid and reliable with an objective scale and has an evidence base to predict those who has the best chance of developing excellence or vice versa. Chapter 4 and Chapter 5 of this thesis elaborates more on the Multi Mini Interviews and their ability to predict dental performance

**Table 2-3 Examples of Motor Predictor tools**

| Predictor tool | Outcome | Predictors variables | Outcome variables |
|---|---|---|---|
| Carving test (Gansky et al., 2004) | No correlation were found between predictor variables and the preclinical score except with the PAT (part of the DAT). | Carving test, GPA, Sessional GPA, DAT | Preclinical restorative score |
| Computerised dental treatment simulator (SIM) (Gray, Deem, Sisson, & Hammrich, 2003) | Correlation were found between SIM score and lab 1 scores and DAT sub-tests. | Lab 1 and 2 scores, DAT sub test (AA, PAT and TS) BCP and GPA | SIM scores |
| Wire bending test (HAM-Man (Kothe et al., 2014)) | Positive correlation was found between the HAM-Man score and Pre-clinical lab | GPA and HAM-Man score | Pre-clinical lab performance |

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| | performance. No correlation was found between GPA and pre-clinical lab performance. | | |
| Interview scores which includes: Embedded figure test (EFT), Revised Minnesota Paper form Board Test (RMPFBT), Dimension Test, NEOPI-R forms for personality, Block test.(Evans & Dirks, 2001) | Positive correlation where found between all predictor variables and the lab score. | Interview scores, GPA, College hours | 3 lab score and combined average score. |
| Wooden tablet, fabric, box (geometric forms inserted in holes, Needle and thread, Wooden boards, Wooden grate, paper and pen, graph paper, playing cards and box with double opening .(Giuliani et al., 2007) | BMDS scores revealed some differences between those having university degree or scientific high school degree than those who studied a classical or vocational high school curriculum. However, no correlation was found | BMDS (Basic manual dexterity score) | Academic level at time of entry, preclinical and clinical performance. |

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|---|---|---|---|
| | between BMDS scores and preclinical and clinical performance | | |
| Individual Dental Education Assistant (IDEA Simulator) (Alice Urbankova, Eber, & Engebretson, 2013) | There was a correlation between Manual dexterity test and the preclinical performance. No correlation was found between PAT and the preclinical scores.<br><br>No association was found between the MDT and the PAT scores. | Manual dexterity test (D-circle) and PAT | Preclinical operative dentistry performance |
| Plastic typodont (prepare class 1 cavity preparation.(Polyzois et al., 2011) | Conventional cavity preparation had limited predictive value for later performance at preclinical level. | Conventional class 1 cavity preparation. | Preclinical performance. |
| Crawford small parts dexterity test (CSPDT).(Boyle & Santelli, 1986) | CSPDT may improve when used with current measures | CSPDT scores and current dental | Preclinical lab scores and overall |

| | | | |
|---|---|---|---|
| | | school admission scores. | dental school performance |
| HAM-Nat test(Kothe et al., 2013) | A correlation was found between HAM-Nat test and preclinical scores. | HAM-Nat score | Preclinical scores. |
| Speeded tweezer dexterity test (Lundergan et al., 2007) | No correlation was found between scores of speeded tweezer dexterity test with clinical performance | Tweezer score and PAT. | First year clinical score.<br>Final year clinical score. |
| Waxing test (Walcott et al., 1986) | Waxing test was a better predictor compared to PAT. | Waxing test score and PAT. | Preclinical performance score |

## 2.3 Simulation

Simulation has been defined as "a technique, not a technology, to replace or amplify real experiences with guided experiences, often immersive in nature that evoke or replicate substantial aspects of the real world in a fully interactive fashion" (Gaba, 2004), while a simulator has been defined as a "device that uses simulation to replace a real-world system or apparatus, allowing users to gain experience and to observe and interact with the simulation via realistic visual, auditory or tactile cues" (Rosen, Long, McGrath, & Greer, 2009).

The principles of simulation were first established in the training of civilian and military pilots and astronauts, but the use of simulation in the health care field became more universal in the early 1990's in the form of digital and mannequin-based, speciality specific simulated scenarios (Buchanan, 2001; Gorman, Meier, & Krummel, 1999; Maliha, Diaz-Siso, Plana, Torroni, & Flores, 2018). Currently, simulators are used in the health field for training emergency room skills (Small et al., 1999), laparoscopic surgery (A. G. Gallagher, McClure, McGuigan, Crothers, & Browning, 1999) and cardiovascular emergency procedures (R. W. Morris & Pybus, 2007).

### 2.3.1 **Simulation based medical education**

Mainly in surgery, the traditional method of teaching of "See one, Do one, Teach one" involves the learner observing a particular procedure once, being expected to be capable of performing that procedure followed by being able to teach another to conduct the procedure. It has been argued that this method should be considered  passé , after receiving a lot of criticism (Qayumi & Vancouver, 2010; Rohrich, 2006; Vozenilek, Huff, Reznek, & Gordon, 2004), considering that patient safety is at risk with this type of approach. Thus, the concept of “learning by doing” has become less satisfactory particularly when invasive procedures and high risk care are required. Restrictions on medical educators have prompted them to seek alternative methods to teach medical knowledge and gain procedural experience (Vozenilek et al., 2004).

From there, simulation based education has re-emerged to bridge the educational gap between theory and practise on real patients and thus acting as an intermediate stage between “see one and do one” and hopefully leading to the transformation to “see one, simulate many, do one competently and teach everyone” (Vozenilek et al., 2004).

It is important to highlight that simulation-based education is not new. The recorded history of simulation in the health professional education stretches over 150 years. In 1974, the London Evening Post advertised for a course on Midwifery that explained that students taking this course would learn on “a contrivance made on the bones or skeleton of a women, with an artificial matrix. The advertisement explained why and how simulation was important in obstetrics education. Students would learn to deliver a baby on the simulator before attending a real labour (the simulator was referred to as the ‘machine’). A simulator would also be used to show what could go wrong and how such problems were best managed and then practise these interventions on a simulator (Owen, 2016). Simulation in health care has a long history but as the twentieth century progressed the use of simulators in health care education with the exception of dentistry and to lesser extend midwifery, seems to have declined so much that when it was re discovered at the end of the twentieth century it was thought to be new. However, it is thought that this re-emergence of simulation has regained interest by educators especially with the advancement of technology aiming to improve performance of the healthcare professionals and the emphasis in patient safety.

In fact over the past decade there have been significant advances in medical visualisation technologies such as Magnetic Resonance Imaging (MRI) and X-ray Computed Tomography (CT scanning). These technologies enabled surgeons to see the internal structure of the human body in a high resolution 3-D. In addition, conventional visualisation methods have been advanced in surgery with an increased utilisation of minimally invasive surgical modalities and shifting away from open surgery where possible. The benefits of minimally invasive surgery include less tissue injury and scarring, quicker recovery time and shorter hospital stays. However, these technologies enhanced surgical techniques introduced a new interface between the surgeon and tissues which requires intensive preparation. This demand led to the adoption of virtual reality simulators along with other simulation modalities in medical training programs. Currently, VR simulators play an important role in the acquisition of sensorimotor skills in surgical education and so far its application in the educational field included: Preclinical skills; General surgery; Laparoscopy surgery; Endoscopic procedures; Neurosurgery; Interventional cardiology and cardiothoracic surgery; Urology; Orthopaedics; Endovascular surgery; Obstetrics and Gynaecology; ENT and Ophthalmology. The advancement of technologies in terms of visualisation technologies and VR simulators are leading the way to a promising and sophisticated highly realistic VR simulators such as Patient Specific Virtual Reality simulators (PSVR) that allow VR simulators to perform patient specific surgical rehearsal based on real patient imaging data (e.g. MRI). These promising PSVR will not only impact performance level but will also minimise complications (Willaert, Aggarwal, Van Herzeele, Cheshire, & Vermassen, 2012).

## 2.3.2 Simulation-based Dental Education

### 2.3.2.1 History of Simulation in Dentistry

In 1894 Oswald Fergus presented the first phantom head simulators by using one metal rod with two brass jaws to aid in an effort to improve realism. Oswald Fergus said:

> "it was expected, and rightly expected, that students should not be let loose to work their will on their suffering fellow creatures without first having acquired a proper efficiency".

Within recent years, the education of dental students has undergone several modifications, some of which have had relatively little impact, while others have had a fundamental effect on course content and the overall approach towards delivery of information and dissemination of skills. Figure 2-6 summarises the timeline of simulations in dental education.

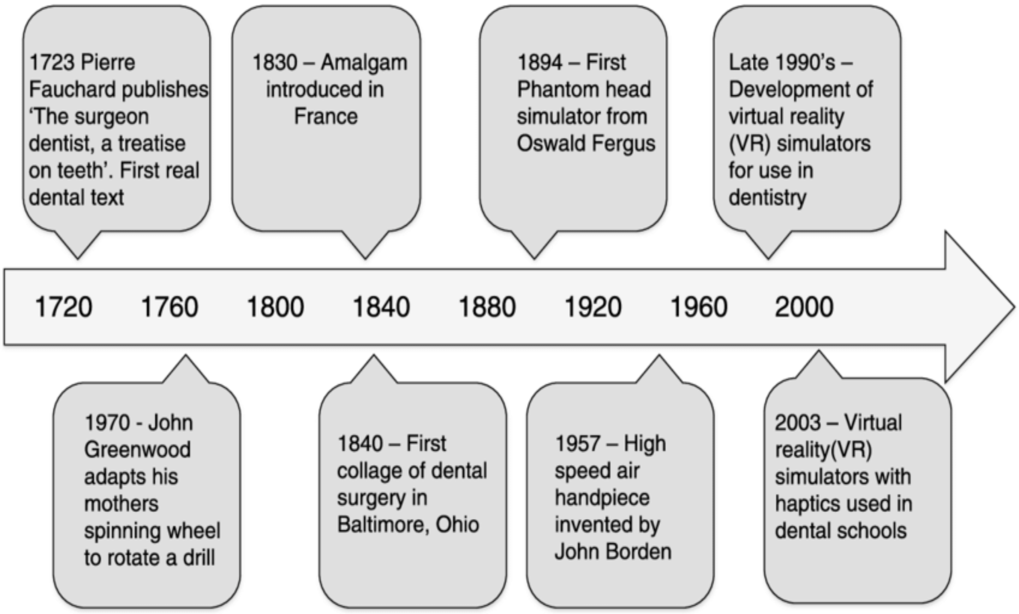


**Figure 2-6** Timeline of simulations in dental education. Used by permission of Lippincott Williams and Wilkins from Perry et al 2015.

### 2.3.2.2 Classification of simulation in Dentistry

#### 2.3.2.2.1 Traditional and contemporary non-computer-assisted simulation

The first college of dental surgery was founded in 1840 in Baltimore, Ohio, United States. At that time, the restorative techniques practiced were using extracted teeth and bench-top simulation. However, a major problem was the availability of natural human teeth for practicing on simulators. In the late 20$^{th}$ century dental education was advanced rapidly as "resin teeth" became much more commonplace. In 1894 Oswald Fergus's introduced the first phantom head, its design has undertaken many refinements and modifications (Fugill, 2013; Suzanne Perry, Bridges, & Burrow, 2015) to improve and expand its utility. These changes have included simulated maxillary and mandibular jaws becoming more realistic, simulating various dental conditions such as periodontitis and caries. Moreover, a full set of individual anterior and posterior plastic teeth that resemble permanent and primary dentition can be modified as required (removed, replaced and adjusted). Simulated clear resin blocks also took part in enhancing dental education through direct visualisation and comparisons of dental procedures (Weine, Kelly, & Lio, 1975). The incorporation of water spray to the phantom head system has also added to the realism of the device (although concerns were raised for possible water line contamination and infection control). Other benefits of these devices include proper handling of dental hand piece and mirror at the same time, the use of finger rest during instrumentation which is an important concept that dental students need to acquire before proceeding into more complex skills (Suzanne Perry et al., 2015).

Currently, phantom head simulators with artificial teeth are considered the gold standard for dental education (particularly 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 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.).

#### 2.3.2.2.2 Computer Assisted Simulation (Augmented Reality)

Augmented reality refers to superimposition of computer-generated graphics over a real-world scene. It aims to add synthetic additives to the real world instead of engaging a person in a world, which is completely generated by a computer (Al-Mussawi & Farid, 2016). These systems are based on computer assisted 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 based on GPS (global positioning system) technology which tracks the position of the manikin jaws and handpiece via LED sensors.

In the majority of these systems, a computer screen is attached to the unit and it shows a 3D representation of the preparation with real-time quantitative feedback and detailed evaluation of performance (compared to an ideal preparation in the database) (LeBlanc, Urbankova, Hadavi, & Lichtenthal, 2004; Levine, DeMaria Jr., Schwartz, & Sim, 2013). The first computer assisted simulator for dental education was developed in the late 1990's (Dutã et al., 2011; Rose, Buchanan, & Sarrett, 1999).

In one study, Jasinevicius et al. (2004) compared computer assisted simulators 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 computer assisted simulators needed significantly less instructional time from the faculty than the other group. Therefore, it has been suggested that these 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 these systems learned faster, performed equally well, and carried out more procedures than students who were trained in traditional laboratories (Buchanan, 2004). This is therefore, 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 simulator especially at the early stages of dental skill acquisition; and advocated the integration of simulation technology at the beginning of the preclinical experience (A. Urbankova, 2010).

Computerized assisted simulation also include 3D printing which involves printing a 3D teeth which simulate biological tissues and caries from digital scans and CT scans that allows the development of anatomically realistic models (Kröger, Dekiff, & Dirksen, 2017; Werz, Zeichner, Berg, Zeilhofer, & Thieringer, 2018).

#### 2.3.2.3 Virtual Reality-based Simulation

Virtual reality technology is described as a system that gives the user a sense of being inside, controlling, and personally interacting with an environment that is three dimensionally simulated or replicated (Schultheis & Rizzo, 2001). Virtual reality depends on two basic features namely, immersion (the act or the sense of being present in a non-real environment) and interaction (the power of the user to interact with the virtual environment). According to these features, virtual reality systems have been classified into three types: non-immersive, semi-immersive, and immersive (Al-Mussawi & Farid, 2016).

Immersive VR simulation is a technology that uses hardware, software and interaction devices to give the operator the psychophysical experience of being surrounded completely by a virtual computer-generated environment. This is the highest level of immersion and is typically produced by a head mounted device. Semi-immersive VR simulation is a system in which the operator wears goggles and sees everything three dimensionally with the help of rear projection walls, down projection floor, speakers at different angles, tracking sensors in the walls and sound /music devices. Non-immersive VR simulation is the least immersive, it allows the operator to be involved with a 3D environment by incorporating a stereo display monitor and glasses (Al-Mussawi & Farid, 2016).

In dentistry, most virtual reality simulators are non-immersive. For a long time, the phantom head simulator was the main simulator in dental schools but due to some of the inherited limitations, new computer-based tools and system have been developed to create virtual reality environments 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, Wesselink, Cox, Quinn, & Shahriari-Rad, 2015).

#### 2.3.2.3.1 High Fidelity haptic simulation

A step-change in the virtual reality world has been produced with advancement of haptic technology and specifically dental simulator development. The haptic system consists of a user, haptic interface (device) and virtual environment. The haptic interface or devices are electromechanical devices with handles that permit the user to experience both the sense of touch and sight when coupled with virtual reality simulators. The touch sensation in the haptic environment can be achieved by machines, humans or both, while the objects and /or environment can be real, virtual or both. These haptic devices present with several features including degree of freedom (DoF), degree of inertia, residential inner friction and resolution. The degree of freedom is determined on the amount of directions the haptic devices can move most commonly; the haptic device has 3-degrees of freedom.

Haptic devices have a certain degree of inertia which usually occurs if the haptic device moves quickly. The residential inner friction is presented as noise. The resolution mainly depends on the amount of feedback per unit distance and the movement area. The amount of feedback needs to be high to enable sufficient detailed textures in the virtual environment, and the movement area needs to be large enough to simulate the actual workspace. At the present, to control interactions, haptic devices use two basic variations: impedance control and admittance control. With Impedance control, the user moves the device and then the details are sent to the computer (measure movement and display force e.g Phantom® and Falcon®). In contrast, in admittance control the device reacts by displacing the force in a proportional distance when the user applies a force (measure force and display movement e.g. Haptic Master ®) (Escobar-Castillejos, Noguez, Neri, Magana, & Benes, 2016).

Through these haptic interface/devices, the user feels, touches and interacts with virtual objects. This ability is known as haptic rendering. Haptic rendering has three types: point based, ray based and 3D object based (made by a group of points, lines and polygons). In medical procedures, rendering of deformable objects is often needed. According to one study, rendering techniques of deformable objects can be divided into two types: geometry based and physics based (Basdogan & Srinivasan, 2002).

Geometry-based technique are rapid and easy to apply and the technique deforms the object based on geometric manipulations. However, it mainly concentrates on visual representations which is not mandatory to represent the underlying mechanical deformation. Physics-based algorithms add physics simulation to the modification of geometry by modelling the physics law involved in object movement and the dynamics of the interaction within it (Escobar-Castillejos et al., 2016). In contrast to geometry-based technique, physics based simulate a realistic performance of deformable objects, thus, they are more expensive compared to geometry based techniques (Escobar-Castillejos et al., 2016).

Dental simulators that incorporate haptic technology that provides realistic feel and touch sensation has changed the way one interacts with virtual objects (Gottlieb et al. 2013). Haptic VR simulators made the simulation experience, almost entirely virtual (with no phantom head, plastic teeth, or real handpiece). These devices have main two benefits over the computer assisted simulator mainly related to the teeth used. The first is that the tooth is virtual which means there is no need to replace the teeth. The second advantage is the manipulation of the teeth density. However, there are of course limitations and some key points needs to be addressed in relation to these devices such as cost benefit ratios, maintenance, how students and staff receive advanced teeth compared to a more traditional typodont, the role of the tutor, how much access students should be given to the simulation and how real simulation  systems need to be for effective education.

The speed of development in the design and features of various haptic dental simulators were 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, Reynolds, Grayden, & Wilson, 2008; Vervoorn et al., 2015).

Currently, there are a number of commercially available haptic dental simulators that have been utilised and investigated in the literature. 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). Table 2-4 and Table 2-5 shows the categories of dental simulation with examples and applications in dentistry, respectively.

**Table 2-4** Categories of dental simulation with examples**.**

| Simulation category | Examples | Manufacturer/ developer | Description |
|---|---|---|---|
| Traditional simulation | Bench top simulator | | Mannequin head (with typodont and plastic teeth) mounted on the laboratory bench, with limited ergonomic features. |
| Contemporary non-computer-assisted simulation | Kavo unit | Kavo Dental GmbH<br>Kavo Dental Corp. | Simulated patient or manikin with workstation, a fully adjustable manikin, electric handpieces and suction. |
| Computer Assisted Simulation (CAS) | DentSim | DenX Ltd. | Phantom head, a set of dental instruments, infrared sensors, overhead infrared camera with a monitor and two computers. |
| Virtual Reality-based simulation | Virtual reality Dental Training System (VRDTS) | Novint Technologies in collaboration with Harvard School of Dental Medicine. | A virtual system consisting of desktop workstation, a phantom Desktop haptic interface, and dental simulation software. |
| High fidelity haptic simulation | Simodont | NISSIN Amsterdam | The simodont system provide a complete virtual oral environment (teeth, instruments) Several dental procedures can be practiced in a virtual environment. |
| | IDSS | A collaboration between the University of Iowa college of Dentistry and Engineering. | It consists of a computer, monitor and force feedback device that focuses on tactile skill development more than psychomotor skill development. |
| | Voxel Man | Voxel-Man group University Medical Center Hamburg-Eppendorf (Germany) | A 3D virtual training device for surgical procedures it includes all teeth and instrument displayed on a 3D screen. |

| | | | |
|---|---|---|---|
| | IDEA | SensAble Technologies | It offers a stylus with six degree freedom attached to a stand that provides the holder with feedback. The unit provides also a 3D animated image on the screen that allows the trainee to practice with tools while providing haptic feedback. |
| | HapTel | A collaboration between Kings College London Dental Institute and Reading University, UK. | It is based on a haptic unit, adapted from a computer gaming device. It includes 2 screens, the software gives flexibility to the drilling position, lightness of touch and foot pedal to control speed of the bur. |
| | PerioSim | Joined work between College of Dentistry and Engineering at University of Illinios at Chicago | Offers 3D, VR graphics and tactile sensation allowing visualisation, detecting and evaluating caries or periodontal diseases in a haptic environment. |

**Table 2-5** Applications of Simulation in dental aspects

| Speciality | Type of procedure | Reference |
|---|---|---|
| Prosthodontics | Diagnosis and treatment planning for implant placement. | (Al-Mussawi & Farid, 2016; X. Chen, Sun, & Liao, 2018; Kinoshita et al., 2016) |
| Maxillofacial Surgery | Perform virtual surgery and generates templates and cutting guides that allow for the precise and expedient recreation of the plan in the operating room.<br>Orthognathic surgery.<br>Le Fort 1 osteotomy.<br>Removal of mandibular molars.<br>Planning and training in paranasal surgery. | (Sohmura et al., 2004; Wu et al., 2014; Yu, Cheng, Cheng, & Shen, 2011) |
| Orthodontics | Treatment planning and movement of teeth | (Alcañiz *et al.*, 1999; Rodrigues *et al.*, 2004) |

| | | |
|---|---|---|
| Periodontics | Training on scaling<br>Diagnosis and treatment of periodontal disease.<br>Differentiation between pathological and normal conditions. | (Mallikarjun, Tiwari, Sathyanarayana, & Devi, 2014) |
| Restorative dentistry | Dental hand skill<br>Dental instrument handling (drilling, exploring, carving and packing)<br>Drilling into enamel, healthy dentin, and carious dentin.<br>Training tooth preparation. | (Buchanan, 2001) |
| Pain control | Delivery of local anaesthesia.<br>Distraction. | (Arane, Behboudi, & Goldman, 2017; Corrêa, Machado, Ranzini, Tori, & Nunes, 2017; Furman et al., 2009; Won et al., 2017) |

## 2.4 Summary

This literature review has covered the key areas of research that will be explored throughout this thesis in the experimental chapters that follow. Specifically, we have covered the processes underlying motor skill acquisition, the extant literature on predicting clinical performance and finally, advances in simulation technology. We now turn to addressing discrete research questions by making use of a state-of-art haptic VR simulator and our background knowledge on motor skills. The overarching objective across these experiments is to generate a body of work that can be used to inform dental educators on the factors that can predict dental performance.

# Chapter 3 Construct Validity of the ‘Simodont’® Haptic Virtual Reality Simulator

## 3.1 Introduction

Virtual reality (VR) technology is becoming ubiquitous in dental training. The dental discipline has a substantial history of using simulation to facilitate the acquisition of the skills necessary for safe practise (Gottlieb et al., 2013). Mannequin-based phantom head simulators with artificial teeth have long been considered as standard pedagogical tools in preclinical teaching (Gottlieb et al., 2013). More recently, with advances in computing power, VR dental simulators are increasingly adopted (Rose et al.1999) to supplement and, potentially, replace these traditional methods (Dutã et al., 2011; Suzanne Perry et al., 2015).

A step-change in VR simulation has come from the integration of haptic technology into simulators as these systems have the potential to provide several advantages over conventional approaches. Advantages include the ability to interact with virtual objects through realistic feel and touch - i.e. known as haptics (Fager & von Wowern, 2004; Gottlieb et al., 2013; Kapoor, Arora, Kapoor, Jayachandran, & Tiwari, 2014).

As highlighted in the introduction, the term “haptics” originally comes from the Greek word haptikos meaning “suitable for touch” and haptesthai meaning “able to lay hold of” (Minogue & Jones, 2006). The term was first introduced by Reves in 1931. Currently, the term haptics generally refers the study of touch and human interaction with the external environment through the sense of touch. Haptic technology also provides students with the ability to feel the various tooth surfaces through force feedback mechanisms and distinguish between soft and hard tissues; potentially useful pedagogical information

(Buchanan, 2001; Dutã et al., 2011; Suzanne Perry et al., 2015). These haptic systems automatically produce kinematic data (performance production measures) that could be used for objective assessment of task performance - information that is not available in conventional training environments (Suebnukarn, Phatthanasathiankul, Sombatweroje, Rhienmora, & Haddawy, 2009).

Whilst there is obvious promise for haptic VR systems, a number of questions regarding the utility of these systems remain (Singapogu, Burg, Burg, Smith, & Eckenrode, 2014). Central to these issues is whether the systems relate to real world dentistry, as training on these systems needs to ultimately translate to the clinic (Issenberg, Mcgaghie, Petrusa, Lee Gordon, & Scalese, 2005; Schaefer et al., 2011). Thus, it is incumbent on those responsible for education in the dental profession to be able to establish the construct validity of a system (Gallagher, Ritter, & Satava, 2003; McDougall, 2007) before it is fully integrated into a dental school's curriculum. Validity is referred to as the ability of a device to measure what it is intended to measure meaning that what a simulator is teaching or evaluating is what it is intended to teach or measure (McDougall, 2007).

Construct validity is specifically defined as "a set of procedures for evaluating a testing instrument based on the degree to which the test items identify the quality, ability, or trait it was designed to measure"( a. G. Gallagher et al., 2003). Construct validity of a simulator refers to its ability to differentiate between technical performances of different groups of learners based on their level of experience (McDougall, 2007). Indeed, this issue (the ability to establish the construct validity of a system before curriculum integration) has recently been identified as a research priority for healthcare simulation (Khera, 2011;

Milburn, Khera, Hornby, Malone, & Fitzgerald, 2012; Motola, Devine, Chung, Sullivan, & Issenberg, 2013).

The ‘Simodont’ (NISSIN, Amsterdam) is one such current state-of-the-art haptic VR simulator and it has been used in the School of Dentistry at the University of Leeds since 2012. The Simodont provides a virtual environment to practise various dental skills in a 3D-oral cavity using virtual teeth, virtual burs and virtual hand instruments. The system has clear face validity as it produces convincing visual and auditory effects during performance (e.g. the sound of the handpiece) to enhance the simulation experience and make it more “realistic” (Cutler et al., 2013; Lyons et al., 2013). However, its construct validity - the ability to which it captures the ability and traits it was designed for (Gallagher et al. 2003), has not yet been established. To this end, the construct validity of the ‘Simodont’ using participants with no previous exposure to the simulator to control for a potentially confounding factor of practise effects has been examined. Here we operationalized construct validity as the ability to be able to differentiate between different levels of real-world dental experience.

## 3.2 Materials and methods

### 3.2.1 Participants

Undergraduate dental students (N=377) enrolled on the dentistry programme at the School of Dentistry at the University of Leeds attended an induction training session on the 'Simodont'. Data were recorded for Years 1 (n = 92), 3 (n = 79), 4 (n = 57) and 5 (n = 61) and retrieved retrospectively and anonymised (Year 2 data were not recorded as the data was not saved in the main server due to technical problems; final sample size of 289). The study was approved by the ethics committees based in the School of Dentistry and School of Psychology at the University of Leeds United Kingdom reference number EDREC/12/030.

### 3.2.2 'Simodont' ® haptic dental simulator

The 'Simodont' is a virtual reality dental simulator (NISSIN, Nieuw Vennep, the Netherlands and ACTA, Academic Centre of Dentistry Amsterdam, Amsterdam, The Netherlands) that consists of a panel PC user interface, 3D display, haptic display, and foot pedal. The haptic display includes a drill gimbal, hand support, space mouse and mirror gimbal. A realistic experience of the true clinical dental environment is simulated through the visual and audio rendering. This includes a true size display of the instrument and tooth rendered on the 3D display. The 'Simodont' courseware (developed by the Academic Centre for Dentistry Amsterdam (ACTA), Amsterdam, Netherlands) provides multiple procedures such as manual dexterity exercises with instant evaluation, operative procedures and crown and bridge preparations for students to practise.

### 3.2.3 Procedure

As part of their induction training on the ‘Simodont’, students were provided with an instruction sheet and verbal instructions from a tutor on how to turn on the system, log in and select tasks. Students were asked to adjust the height of the chair and the unit to a position that felt comfortable and wear stereoscopic spectacles. Participants were given an opportunity to ask any questions at any point during the training. Students were then provided with six manual dexterity exercises (displayed on the screen), from which the task–relevant instruments were then selected.

All participants engaged in a manual dexterity exercise which approximated the basic requirements of most dental procedures. The task involved use of a dental handpiece to remove a target “red zone”, presented as a cross-shape in the middle of a block, whilst attempting to minimise removal of leeway zones (the ‘safe’ outer areas of the block) as much as possible (see Figure 3-1 for further details).

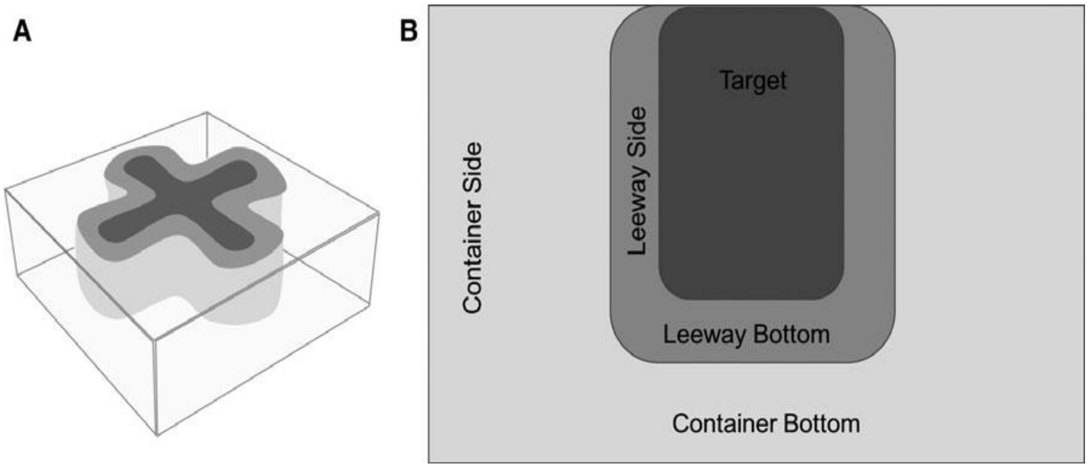


**Figure 3-1.**Schematic drawing of the task**.** (A) Schematic drawing of one of the abstract shapes available in the manual dexterity training section of the 'Simodont' courseware. (B) Cross-section of the exercise illustrating the location of a Target, the area of the Leeway (sides and bottom) and Container (sides and bottom).

Real-time feedback on performance was presented on a computer monitor attached to the device throughout the task. The feedback information included a percentage score for each of the following: target (task completion percentage), error scores (leeway bottom, leeway sides, container bottom and container sides), and drill time (in seconds). Participants were instructed that the aim of the task was to remove a minimum of sixty percent of the red zone without touching the beige zone. Once this had been achieved, the students could stop the drilling and end the task. The students were free to take as many attempts as they felt necessary to reach the target score. All students were able to remove 60% of the target, however only the best performance (target > 60%, not touching the container zone with shorter time to perform the task) for each participant was used for data analysis.

### 3.2.4 **Data Analysis**

For statistical analysis, performance on outcome variables: Time (in seconds), Leeway bottom, Leeway sides (quantified as percentages) and finally, a Composite Score that captured speed-accuracy trade-offs in performance were measured.

The composite measure was calculated by multiplying the log of the sum of the leeway errors (sides + bottom) by the log of the amount of time taken to complete the task so that lower scores indicate better performance. All variables were tested for normality to ensure the data met requirements for valid analysis of variance (ANOVA). Where data were not normally distributed, a transformation of the outcome variable was performed.

When a significant difference of ANOVA ($p < .05$) was found between the groups, Bonferroni corrected post hoc comparisons were performed. Partial eta squared values ($\eta_p^2$) are reported to indicate effect size. ANOVAs were conducted using IBM SPSS version 20 (IBM, Armonk, NY, USA), and the linear regression was performed using R version 3.1.3 (R Development Core Team, 2015)

## 3.3 Results

A one-way ANOVA was conducted to compare student performance according to their year of progression for all outcome variables .A significant main effect of the year of study on the Composite Score was found [F(3285) = 6.36, $p$ < .001, $\eta_p^2$ 0.06],Time [F(3285) = 7.08, $p$ < .001, $\eta_p^2$ 0.07], Leeway Bottom [F(3284) = 8.95, $p$ < .001, $\eta_p^2$ 0.09], Leeway Sides [F(3284) = 7.51, $p$ < .001, $\eta_p^2$ 0.07]. For brevity, only the statistically significant comparisons for each variable are described and the data are plotted in Figure 3-2.

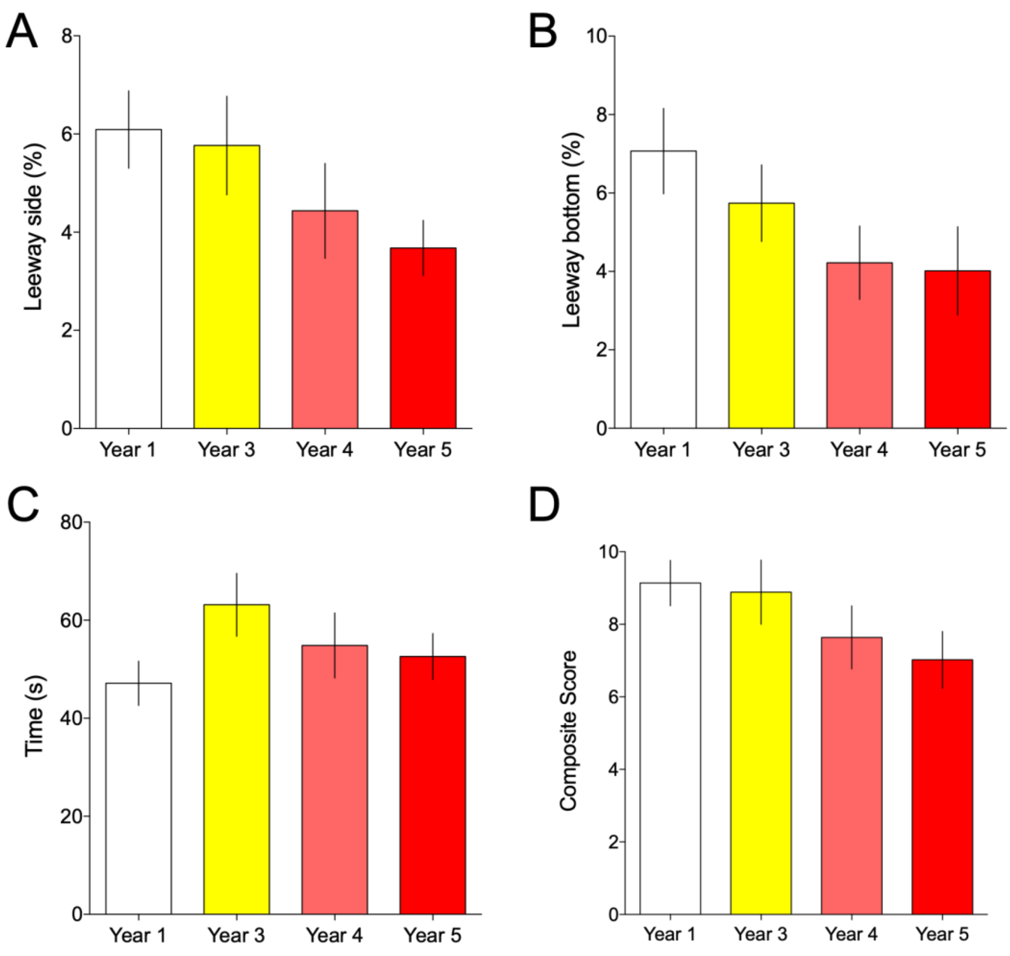


**Figure 3-2** Performance measures as a function of Training Year are plotted separately for (A) Leeway Sides, (B) Leeway Bottom, (C) Time and (D) the Composite Score. Error bars represent 95% confidence intervals.

For the Composite Score, post hoc analysis revealed that Year 1 performance was significantly different to Year 4 ($p$ = 0.05) and Year 5 ($p$ < 0.001) and Year 3 was significantly different to Year 5 ($p$ = 0. 008). For Time, the Year 3 students took significantly longer to complete the task relative to Year 1 ($p$ < 0.001). In the error measures, the Leeway Side variable, Year 1 performance was significantly different to Year 4 ($p$ = 0.006) and 5 ($p$ < 0.001). Year 3 also made more Leeway Side drilling relative to Year 5 ($p$ = 0.027). This pattern of results was similar in the Leeway Bottom variable, with Year 1 making more drilling in this area relative to Years 4 (p = 0.001) and 5 ($p$ < 0.001). In addition to this, Year 3 performance on this outcome variable compared to Year 5 approached the significant threshold ($p$ = 0.056). meaning that it did not meet the predetermined level of significance which was 0.05 but was close.

Finally, to examine whether real-world dental experience could predict performance on simulator, the Composite Score described above was used and this value was regressed against the year of the programme of study (r = -0.229, $p$ < 0.001). The results showed that the year of the programme of study was a statistically significant predictor of performance, although it explained only a small amount of the variance in this measure (see Table 3-1). The regression analysis indicated that for every 1-unit increase in the year of the programme of study, the performance on the Composite Score decreased by the unstandardised beta coefficient value of 0.519.

**Table 3-1** Predicting VR performance from the year of programme of study

| Variable | B | SE | β | t | Sig. | Adjusted $R^2$ |
|---|---|---|---|---|---|---|
| **Constant** | 9.88 | 0.13 | | 22.65 | <0.001 | |
| **Year** | -0.519 | 0.04 | -0.229 | 3.99 | <0.001 | 0.049 |

## 3.4 Discussion

This study investigated the ability of the ‘Simodont’ VR system to detect differences in motor performance between dental students with different levels of experience. As far as we are aware, this is the first investigation on the construct validity of this virtual reality simulator. The results showed that Year 3, 4 and 5 students scored better than Year 1 students in the composite measure of performance. The difference in performance between Years 3, 4 and 5 was not significantly different, although the mean value grew linearly as dental experience increased. For the time taken to complete the task, a significant difference was only found between Year 1 and 3. Specifically, Year 3 took the longest time to complete the task, whilst Year 1 took the shortest time. Years 4 and 5 took less time to complete the task compared to Year 3. The overall scores and the task duration showed convergent validity. The performance of dental students improved as their level of experience increased. Likewise, the time taken to complete the task decreased as their level of experience increased- as shown by the differences between Years 3, 4 and 5.

These data align well with the current understanding of the stages involved in motor skill acquisition (Diedrichsen and Kornysheva, 2015). Early learning, which could last from minutes to months, is achieved by the students as they become able to produce movements using less motor planning or preparation time. This shift in the time-accuracy trade-off is a hallmark of motor skill learning, followed by subsequent automatization (skill learning) which can occur at an execution level (through the formation of a new motor primitive) or at an intermediate level (allowing generation of novel behaviour, hierarchical chunking of actions, sequences and modular representation) (Diedrichsen & Kornysheva, 2015).

The current data show that students take less time to perform a task, but are less accurate in their attempts to do so when they are at the beginning of dental education. They then start to sacrifice time for accuracy (performing the task takes longer) as demonstrated by the Year 3 results, displaying a speed-accuracy trade-off. This is considered the first phase of learning whereby students try to understand the activity and concentrate on avoiding mistakes (Reis et al., 2009; Shmuelof et al., 2012; Telgen et al., 2014; Yarrow, Brown, & Krakauer, 2009). The time taken to perform the task decreases and accuracy improves as the students gain more experience in years 4 and 5. This could be related to the middle phase of learning; gross mistakes decrease, performance appears smoother, and learners no longer need to concentrate as hard to perform at an acceptable level (Reis et al., 2009; Shmuelof et al., 2012; Telgen et al., 2014; Yarrow et al., 2009). This is in agreement with previous work which reports that performance improves with the amount of practice and is an index of expertise, whereas duration tends to decrease as the performer gains more experience (Diedrichsen & Kornysheva, 2015; K Anders Ericsson, 2004).

Overall, these findings show that the ‘Simodont’ is able to capture performance between novice and experienced dental students (such as between Year 1 and Year 4 or between Year 1 and Year 5), but not between performance of experienced trainees with varying levels of experience (e.g. comparisons between Year 1 and Year 3 or Year 3 and Year 4). It is however, unlikely that there is no real difference between these years as Year 4 and Year 5 receive substantial clinical experience. Moreover, other studies have shown that, in terms of manual dexterity at least, there should be a clear difference between year groups (Wierinck, Puttemans, Swinnen, & van Steenberghe, 2007).

In future work, it may be useful to increase task demands and examine whether the 'Simodont' is sensitive to this manipulation. For example, future studies could ask participants to obtain a higher percentage of target removal and/or lower error rates, introduce visual transformations such as mirror tasks, restrict the amount of time available to complete the task or include the number of attempts to reach the target score.

Previous studies have also attempted to capture motor performance using simulators (G Ben-Gal, Weiss, Gafni, & Ziv, 2013; E. R. Wierinck et al., 2007), but have mainly concentrated on broader differences between experience (such as dental students, dentists and non-dentists), whereas in this study the main aim was to capture finer differences in motor performance (between dental student year groups). This approach will allow to start the process of establishing the convergent validity of 'Simodont'.

## 3.5 Conclusion

The ‘Simodont’ has shown sensitivity to performance differences between novice and experienced students. Thus, the ‘Simodont’ has the potential in stratifying different levels of dental students’ performance (with the performance metrics that it automatically generates). The ‘Simodont’ has shown convergent validity, suggesting it has good potential for measuring dental performance, educating students,  as a tool for the dental selection process, prediction and monitoring of dental performance. Nevertheless, a variety of tasks of differing difficulty are likely to be required for fine graded discrimination (where easier tasks may have discriminatory ability at the novice end of the spectrum and vice versa). The present study suggests that research on this topic is highly justified and could lead to a step change in dental education practice.

# Chapter 4 Assessment of the Multiple-Mini-Interview (MMI) selection process

## 4.1 Introduction

The process of undergraduate dental education is both lengthy (typically 5 years) and expensive. The identification of students with the necessary aptitude for the profession is essential (Polyzois et al., 2011) . The selection of the best suited students will ultimately ensure that the best educated graduates will be entering the dental profession, and thereby benefit patient care for the public in the future (see Mon-Williams *et al.*, 2015; Mushtaq *et al.*, 2016 for recent commentaries on these issues).

Some dental educationalists have developed lists of domains required for prospective students to demonstrate as they become competent dental practitioners. The purpose of these lists is to guide processes aimed at identifying those students with the most potential. For example, the American Dental Education Association (ADEA) has identified the following skills as essential for a dental student: critical thinking, professionalism, communication, interpersonal skill, health promotion, practice management, informatics and patient care (ADEA House of Delegates, 2011).

Similarly, Cowpe et al (2010) dentified seven domains in the Profile and Competence for the graduating European dentist (2010), comprising: professionalism; interpersonal skills; communication and social skills; knowledge base, information and information literacy; clinical information gathering; diagnosis and treatment planning; therapy: establishing and maintaining oral health; prevention and health promotion (Cowpe et al., 2010), a list that has subsequently been approved by the General Assembly of the

Association for Dental Education in Europe (ADEE). Both associations share similar domain values but with some differences in the terminologies or subdivisions.

The General Dental Council of the UK (GDC) has also set up learning outcomes for potential registrants which are grouped in four domains: clinical, communication, professionalism and management and leadership , with nine key principles of Standards for the Dental team (GDC 2012). The issue is then how to best evaluate the core traits that will allow a student to take advantage of opportunities to acquire these skills over their educational journey.

The traditional approach to undergraduate selection in UK dental schools has been through unstructured interviews. This method has strong face validity (J. G. Morris, 1999) but has many failings including a lack of standardisation, poor predictive value and potential for interviewer and social bias (Kreiter, Yin, Solow, & Brennan, 2004; Razack et al., 2009). Moreover, unstructured interviews fail to systematically capture the wide-ranging skills required for dentistry. These problems have led many dental schools to switch to standardised selection processes designed to map to the specific set of skills and aptitudes that are believed to be required for dentistry.

Structured interviews have been gaining traction in recent years (Eva & Macala, 2014; Kay, Bennett, Allison, & Coombes, 2010). Perhaps the most popular form of structured interview is the ‘Multiple Mini Interview’ (MMI). MMIs involve short independent assessments, typically in timed circuits. These assessments are designed to resemble the Objective Structured Clinical Examination (OSCE) and are rated by one or two assessors (Eva et al., 2004). MMIs have been successfully introduced by several health disciplines across the world as well as within a number of dental schools (Alaki, Yamany, Shinawi, Hassan, & Tekian, 2016; Dowell, Lynch, Till, Kumwenda, & Husbands, 2012; C. Roberts, Zoanetti, & Rothnie, 2009).

Importantly, MMIs have been found to be fair and acceptable to students, with many students reporting they enjoyed this interview format, and stating that the process allowed them to be competitive. Students also reported that MMIs helped them present their strengths free from any social bias (Dowell et al., 2012; Lemay, Lockyer, Collin, & Brownell, 2007; Pau et al., 2013; Razack et al., 2009). The MMIs are also perceived positively by assessors who have reported that MMIs are effective and provide a format that allow them to evaluate soft skills, candidate abilities and thought processes. The assessors suggested that overall MMIs evaluate a better range of competencies when compared to traditional interviews (Campagna-Vaillancourt, Manoukian, Razack, & Nguyen, 2014; Oyler, Smith, Elson, Bush, & Cook, 2014). In terms of reliability, recent reviews for student selection in health profession training have suggested that MMIs have moderate to high reliability and have the added benefit of allowing additional analyses to be conducted (Cleland et al., 2012; Pau et al., 2013). The effectiveness of MMIs in predicting future undergraduate and postgraduate performance has also been reported to be good (Eva et al., 2012; Lee et al., 2016).

In dentistry, a number of studies focusing on the perception of applicants and interviewers (McAndrew & Ellis, 2012, 2013) have suggested that MMIs are potentially a better predictor of ultimate dental performance than traditional interviews (Foley & Hijazi, 2013; McAndrew et al., 2017) and indicate that MMIs are particularly useful in testing cognitive reasoning skills (C. Roberts et al., 2009). The potential advantages of MMIs have meant this selection approach has been adopted by a number of dental schools within the UK. Nevertheless, no studies have been conducted to establish exactly what these stations are assessing (i.e. what are the skills and abilities that these stations are capturing). Nor have any studies ventured into the related issue of whether the purported assessment at a given station corresponds to the appropriate underlying construct. From here, it would be possible to take an important step in promoting an evidence-based approach to prospective student assessment by providing a systematic examination of the underlying factors being assessed in a current MMI.

The main aim of this study is to identify the factors and traits that is being captured by this assessment approach and how they map on to the competencies required for dentistry and the implications for the efficiency and efficacy of this interview process.

## 4.2 Materials and methods

### 4.2.1 Admission process

Applicants were selected for interview based on their UCAS (Universities and Colleges Admissions Service) form. The UCAS form assigns numerical scores for each of its components, which include academic performance, medical experience, work experience, activities and reference report and each application was ranked. The marking was performed by experienced members of the admission team and marked twice to ensure there were no discrepancies.

### 4.2.2 Participants

From a total of 1,409 applicants, 245 candidates were invited to compete via MMIs for a place on the five-year Master and Bachelor of Dental Surgery and Bachelor of Science (MChD/ BChD, BSc) programme at the University of Leeds, UK for 2013/14 entry. Two hundred and thirty-nine students attended and eighty-seven were successful in their application. The data were retrospectively retrieved (anonymised) for all 239 applicants for the purpose of this study (approved by the School of Dentistry Research Ethics Committee at the University of Leeds, Reference: 271016/IM/216).

### 4.2.3 MMI

The MMI scenarios were developed to assess different domains of competency with a focus on non-cognitive skills. The scenarios were determined by academics, the admissions teams and professional/specialist staff within the dental school. Retrospective probing of the members of the team involved in scenario selection revealed that the decisions were based largely on clinical experience of the requirements for successful dental practice. A list of the ten stations, the skills these stations were purported to assess, and the tasks employed to assess these skills is presented in Table 4-1 .

**Table 4-1** Details of skills and the procedure being assessed by each station.

| Station Name | Purported skills assessed | Procedure |
|---|---|---|
| **Observation** | Observation skills and ability to accurately describe objects from memory | Candidates were asked to look at a collection of objects for 1 ½ minutes. They were able to touch/rearrange/pick items if they wish. At the end of 1 ½ minutes, the objects were hidden and they had 2 minutes to list all the objects they remembered seeing. Of the items which they remembered, the examiner asked them to describe some of them in greater details. |
| **Ethics** | Ethical awareness and reasoning | Candidates were given an article to read carefully and asked to discuss any issues which arise from the situation. They were expected to identify the ethical dilemmas posed and discuss the pros and cons of any possible suggestions or solutions. |
| **Presentation** | Communication skills | Candidates were required to give a 5-minute presentation. The remaining 2 minutes were for the examiner to ask questions to the candidate in relation to their presentation. |
| **Origami** | Ability to follow instructions and manual dexterity | Candidates were given a sheet of origami paper and a workbook with pictures and instructions showing how to create an origami shape. |
| **Insight** | Insight into issues | Candidates were provided with a picture or a scenario and asked to discuss barriers or issues that they might have if they had to access/get healthcare. |
| **Communication** | Communication skills and empathy | Candidates were required to communicate and explain to a disbelieving and upset mother that her child had several decayed teeth. |
| **Interpretation** | Analytical and data interpretation skills | Candidates were given 2 minutes to read through the study information after which the examiner asked to discuss the study and data to probe their understanding. |

| | | |
|---|---|---|
| **Tangram** | Communicate complexed instructions | Candidates were provided with a photograph of an object made of wooden blocks of various shapes. Their task was to explain to the student examiner how to construct the object using the same shaped wooden pieces (not coloured) that they had in front of them. |
| **CKAT** | Manual dexterity | Candidates needed to complete the Kinematic Assessment Tool (KAT)- a standardised motor test battery on a tablet PC (using a stylus) to assess fundamental sensorimotor skills. The task involved: (1) tracking a moving dot; (2) aiming at a series of dots that appeared serially in different locations; and finally; (3) carefully tracing a shape that appeared on the screen. |
| **Simodont** | Manual dexterity | The candidates were required to complete a manual dexterity exercise on a virtual reality (VR) haptic simulator. An abstract task was designed to simulate the requirements of dental surgery. The task involved using the dental instruments on the VR system to remove as much of the red coloured zone as possible on a virtual object, whilst trying to avoid the green and beige zones as much as possible. |

The stations were run by dental school staff (including clinical academics and researchers) and current undergraduate dental students from the fourth and fifth year. All staff members and students who took part in the MMIs received extensive training beforehand. The staff had multiple practise runs with simulated students to practise the scoring system (the purpose of this simulation run was to ensure smooth running of the stations and examiners could familiarize themselves with the scoring system) and received a briefing on the days of the interviews.

### 4.2.4 **Procedure**

Each circuit took eight students and there were four circuits per session (half day). Each station lasted between 7-8 minutes. At each station, one minute was given for applicants to make themselves comfortable, be greeted by the examiner and presented with the scenario. The applicants were given five minutes to perform the task. Candidates had one minute to move between stations. Each station was rated by one or two assessors. The interactive digital stations took around 20 minutes each to complete (10 minutes to explain the task and 10 minutes to perform the task). The total MMI time was 104 minutes with approximately 64 candidates being examined per day. The marking criteria for each station are described in Appendix A1.

### 4.2.5 Data Analysis

For statistical analysis, we measured performance on all ten items. All the items were tested for normality and sampling adequacy to ensure the data met the requirements for factor analysis. Where data were not normally distributed, a transformation of the outcome variable was performed. A correlation matrix was created to determine the relationship between the variables. A parallel analysis method along with a scree plot were selected to be the extraction methods for determining the number of factors to extract over the eigenvalue rule (Ruscio & Roche, 2012). The parallel analysis was followed by factor rotation to determine the loadings of each item on the factors. All data were analysed using R version 3.3.1.

### 4.3 Results

A factor analysis was conducted on ten items with orthogonal rotation (varimax). The Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy verified the sampling adequacy for the analysis (KMO= 0.69, and all KMO values for individual items were > 0.5). This demonstrated that it was acceptable to proceed with the analysis. Bartlett's test of sphericity (which tests the overall significance of all the correlations within the correlation matrix) was significant ($x^2$ =189.09, df = 45, $p < .001$), indicating that it was appropriate to use a factor analytic model on this dataset.

All ten items entered the factor analysis together. Using the parameters of this study the parallel analysis method suggested that two factors be retained. Inspection of the scree plot supported the results of the parallel analysis suggesting that two factors gave the most interpretable solution. An orthogonal rotation (varimax) was then performed since the factors were expected to have low correlation to determine the loading strength of each item to the factor. Inspection of the factor correlation matrix showed non-zero correlation between the proposed factors. For the interpretation of the factors, the pattern matrix was used following the analysis. This analysis revealed that all items loaded significantly on one of the factors Figure 4-1 demonstrates the loading strength of each item to the factor.

The results of the factor analysis of the ten items used in the current study revealed two factors were sufficient to explain the underlying structure of the MMIs. The first factor had an eigenvalue of 1.37 and accounted for 14.6% of the variance in the data. The second factor had an eigenvalue of 0.52 and accounted for a further 6.3% of the variance.

The first factor seems to reflect soft skills as all six items (presentation, memory, ethics, interpretation, and insight) related to the ability to communicate (with the ability to show empathy), analyse and interpret data, describe things, show ethical awareness and reasoning and give their personal insight into issues. Thus, factor 1 was labelled as “soft skill”. The second factor appeared to represent visuomotor skills as the four items origami, simulator performance, CKAT and tangram loaded most highly on it. All four items related to manual dexterity performance with the ability to follow complexed instructions, thus, factor 2 was labelled as “visuomotor”.

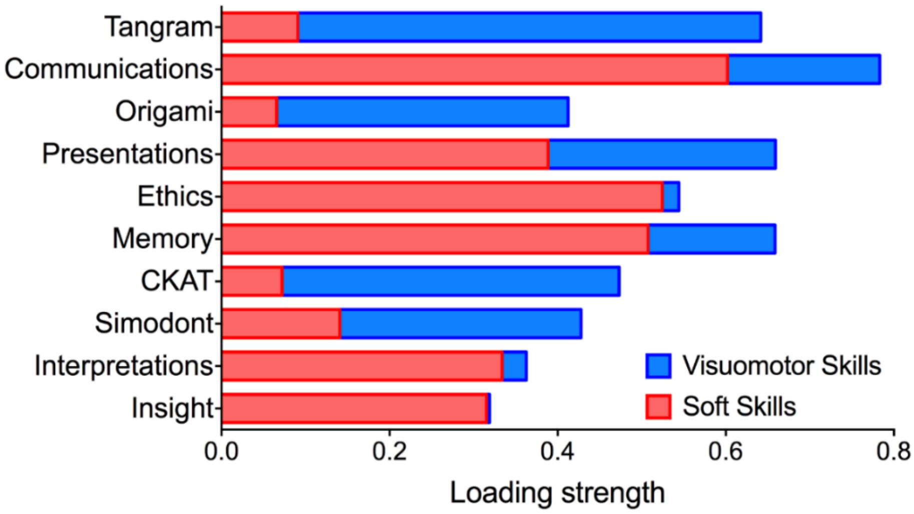


**Figure 4-1** Factor loadings of the ten items Memory, Ethics, Presentation, Origami, Insight, Communication, Interpretation, Tangram, ‘Simodont’ and CKAT (Clinical Kinematic Assessment Test) across the 2 factors of ‘soft skills’ and ‘visuomotor skills’. Factor Loadings represents the variance explained by each item on the particular factor.

## 4.4 Discussion

The present study was based at the School of Dentistry at the University of Leeds, where ten selected scenarios were deemed to be useful tasks for identifying the most suitable students for admission to the Dental Surgery programme. This reflects an approach that has been adopted by many dental schools throughout the UK. While there is a degree of sharing good practice/approaches used across different dental schools, ultimately each dental school has its own MMI structure (i.e. each school will use different types and numbers of scenarios and the scoring of performance will differ across institutions (Dowell et al., 2012; Lemay et al., 2007). This situation suggests that there is a need to evaluate the scenarios used and conduct formal statistical tests to ensure that dental schools are using the best possible assessment procedures, with the ultimate goal of establishing an optimal assessment procedure that could be used by all.

An evaluation of the research literature to date suggests that there has been little formal evaluation of MMIs within dental schools to allow a formal evaluation of the individual tests and their psychometric properties and enable evidence-based improvements in the selection process despite the nature of MMIs (and the wealth of data collected on an annual basis). For example, only one study was found on this topic (that investigated the influence of gender and starting station in the MMI used for dental school entry (Barbour & Sandy, 2014)).

In medicine, there have been studies that have investigated the MMI test characteristics when station type was manipulated (Eva & Macala, 2014) and the effect of examiners' systematic differences in the rating pattern for candidates' scores and selection (Till, Myford, & Dowell, 2013). Eva et al noted that changes to the structure of the stations can yield better outcomes (e.g. behavioural interview stations were found to be better than unstructured situational judgement and free-form stations Eva and Macala, 2014). These types of studies indicate the potential for statistical evaluation of the assessment process, with the data then enabling improvements to be implemented on the basis of objective findings. Nevertheless, there is a lack of reported research into the properties of individual tests and the underlying factors (traits) that are captured by the MMI stations.

The present study investigated the number of factors that underpinned performance across the MMI stations and examined the statistical relationship between the stations. The correlation analyses showed low correlations, but the factor analysis revealed two distinct factors that could explain the underlying structure of the MMIs. The factors were labelled as ‘soft skills’ and ‘sensorimotor’ ability. If the design of the MMI is accepted to have a good face validity for the experienced admissions team, then it is possible to conclude that these are two fundamental factors that are essential in prospective dental students (along with academic capability which is typically assessed via standardised national examinations within the UK). This result tallies well with the general consensus across the dental discipline regarding the critical attributes that are required by dental student. For example, a review paper highlighted the importance of these skills in dental practice and suggested that ‘soft skills’ increase confidence, professionalism, co-ordination, friendliness and optimism in an individual (Dalaya, Ishaquddin, Ghadage, & Hatte, 2015). The review also suggested that a combination of soft and motor skills are important for patient management, dental practice and business management.

The identification of these two fundamental traits is important because it provides an evidence-based rationale for the factors that MMIs need to capture. In turn, this allows greater efficiencies within MMI design. For example, the data suggest that fewer stations may be required to capture ‘soft skills’ (given that six stations load onto this factor). There are advantages to some redundancy in the stations (e.g. a student may perform poorly on an initial station because of nerves) but there are clear economic advantages to having the lowest possible number of tests for each domain of competence as this will help in covering more traits. This will be further decided when mapping these stations with eventual student performance and thereby a clear view on how these stations could be redesigned by either refining or combining better stations and rejecting poorer ones will be achieved. This mechanism can provide a tool for assessment of these MMI stations to robustly measure broader competency traits and identify the tests that have the best construct validity for these domains. MMIs typically include some form of assessment of motor skills as manual dexterity is an integral part of dental practice (L. M. S. Al-Saud et al., 2016; Gansky et al., 2004). Unfortunately, a number of motor skill assessments rely on poorly validated instruments that require subjective evaluations of performance and that are intrinsically unreliable.

The results of the current study suggest that it would be highly beneficial for dental schools to adopt and evaluate precise and objective measures of sensorimotor ability. It may also be useful to develop tests that combine the skilled control of the hands together with higher-order cognitive abilities (such as decision making), as this reflects the reality of how motor control is implemented within dental clinics. The MMIs within the present study included a virtual reality simulator that required a naturalistic combination of sensorimotor and decision making skills and this may be a particularly useful station (Mirghani et al., 2018). In the future, it will be of interest to determine which of the existing stations provides the best prediction of undergraduate performance (as indexed by performance on the myriad of tests conducted throughout the undergraduate degree). The great advantage of the MMI system is that the usefulness of the stations can be evaluated over time and assessments altered on the basis of this evidence. The present study provides a small, but important, first step in the statistical evaluation of dentistry MMI stations.

## 4.5 Conclusion

A well-established interview technique for entry to a UK dental school was subjected to factor analysis. The results showed that the interview process captured two fundamental traits across ten assessment stations. Further studies involving these stations and their ability to predict undergraduate performance will allow the iterative and methodical improvement of station design. Thus, such data and analyses will have important implications for the design and refinement of the entry processes for dental schools across the world.

# Chapter 5 Changes in sensorimotor skill over the course of Undergraduate programme of Dental Surgery

## 5.1 Introduction

There are numerous advantages to creating objective measures of an individual's underlying motor ability. The difficulty with creating such measures is that motor skills can be trained. There is no doubt that dentists get a lot of practise over a lifetime of clinical work given their working in small confined spaces (e.g. the oral cavity) and manipulating instruments with millimetres of precision. But does a dentist's fundamental manual dexterity change as a result of this practise? In other words, through practising a specific fine motor skill on a weekly basis, are there changes to the systems that measure the execution of fine motor skills?

A key feature of human learning is that the largest changes occur in the early stages of the process (as can be visualised on learning curves). Thus, it holds to reason that the first few years of clinical practise will see the greatest changes (if any) in measures of manual dexterity over the course of a dental undergraduate programme.

Previous investigations into the motor learning curve for dentistry have only focussed on small durations of time. For example, a recent study demonstrated statistically reliable improvements observed after only 2-3 weeks of training and, after 12 weeks of observation, there was no plateau in performance (Gilad Ben-Gal et al., 2017). Moreover, the students who performed better at the outset performed better and needed less time to reach targets, whilst the lowest performing students remained low throughout the entire study (Gilad Ben-Gal et al., 2017). Given that an undergraduate degree typically involves five years of study, there is a clear gap in our knowledge of the characteristics of the remainder of this learning curve.

In general, studies have stressed the importance of assessing manual dexterity over time through valid manual dexterity tests (de Andrés, Sánchez, Hidalgo, & Díaz, 2004; Luck et al., 2000). These studies have also typically concluded that manual dexterity tests are useful in monitoring and assessing improvement or detriment in manual dexterity over a period of time (de Andrés et al., 2004; Luck et al., 2000). This is particularly vital in dentistry as dental students need to acquire fine motor skills during their dental programme in order to excel. This begs the question of how we might reliably assess changes in manual dexterity over time?

Human motor control is classically inspected by measuring movements in response to the presentation of some visual stimuli in a controlled task. The majority of laboratory-based techniques designed to capture the movement of the hands are categorised based on the sensory technology employed: mechanical, optical, magnetic, inertial and graphical. One major drawback common to these hand movement recording devices is the fact that they are not fully integrated with visual display systems. The Kinematic Assessment Tool (KAT) provides an integrated system for human movement measurement and analysis through the controlled presentation of interactive visual stimuli (Culmer, Levesley, Mon-Williams, & Williams, 2009). This test was specifically designed as a solution that would allow the integration of the visual display software with accurate measures of end-point hand control and is completed on a touch-screen tablet PC using a hand-held stylus.

Validation studies have shown that KAT provides a detailed kinematic feedback on performance comparable to laboratory motion capture systems

(Shire et al., 2016). The task battery (comprising three different tasks - tracking, aiming and tracing) is designed to measure core manual dexterity skills and taps into sensorimotor processes central to the control required for other ‘real-life’ tasks such as handwriting. The system has been tested on thousands of children and adults since its development in 2009 and has shown itself to be capable of distinguishing between different level of motor coordination on the basis of functional ability (Flatters, Hill, Williams, Barber, & Mon-Williams, 2014; Flatters, Mushtaq, et al., 2014). As such, it makes an ideal assessment for testing manual dexterity development in dental students across their dental programme.

The aim of this study was to investigate whether there were any changes in the performance of dental students as measured by the KAT by comparing the manual dexterity scores of dental students at the University of Leeds School of Dentistry at the Multiple-Mini-Interview stage (Year 0, i.e. prior to enrolling on the dental undergraduate programme) and in the fifth year of their study. In other words, we investigated the test-retest reliability of the KAT system.

## 5.2 Material and methods

### 5.2.1 Participants

Undergraduate dental students (N=30) enrolled on the dentistry MChD/BChD, BSc programme at the School of Dentistry at the University of Leeds 2013/2014 entry participated in this study. After gaining approval from participants, data for the KAT MMI scores (recorded in December 2013) were retrospectively retrieved. Data for KAT at fifth year performance were recorded in December 2018 and then subsequently anonymised. The study was approved by the ethics committees based in the School of Dentistry and School of Psychology at the University of Leeds, United Kingdom DREC ref: 271016/IM/216.

### 5.2.2 The Kinematic Assessment Tool

The KAT is an experimentally validated system capable of providing accurate and repeatable measures of kinematic performance in a package that is portable, rugged, and operable. KAT consists of a laptop screen that rotates and folds back to provide a horizontal display and 'writing' surface using integrated sensors that measure the planar position of a custom stylus.

The test battery was designed and presented using the KAT, a custom software package specialised for presenting interactive visual stimuli on a tablet laptop computer screen, whilst simultaneously recording participants' kinematic responses to these stimuli via interactions with the screen using a handheld stylus (Culmer et al., 2009). The KAT software has been implemented using a software development environment: LabVIEW (Version 8.2.1, National Instruments™). The KAT battery was implemented on Toshiba tablet portable computers (Portege M700-13P, screen size: 303×190 mm, 1280×800 pixels, 32-bit colour, 60 Hz refresh rate) with a pen-shaped stylus (140×9 mm diameter) used as an input device.

The KAT framework is constructed around the delivery of interactive kinematic assessment trials in which visual stimuli are coordinated with respect to movement of the input device. All the tasks in the KAT require the use of a stylus pen and these sub-tests are detailed next.

#### 5.2.2.1 KAT Sub-Tests

The KAT test battery consisted of three tasks (tracking a moving dot, aiming between a series of dots and tracing along a path), all performed with a pen stylus on a tablet computer (during every subtest the position of the stylus is recorded at a rate of 120 Hz, with a 10 Hz dual-pass Butterworth filter applied to the raw positional data at the end of each testing session).

### 5.2.3 Tracking

This sub-test comprised of two trials, the first trial was without guidelines while the second trial included guidelines (3mm wide). Initially, participants started by placing the stylus tip on a motionless dot (10 mm diameter) presented in the centre of the tablet's screen. After a second's delay the dot started moving across the screen in a figure of eight motion (height = 55mm and width = 110mm) for 84 seconds for a total of nine ‘Figure of 8’ motions transitioning from slow to medium to fast each consisting of 3 revolutions. At this stage the participants were instructed to keep the tip of the stylus as close as possible to the dot's centre for the remainder of the trial see Figure 5-1a.

### 5.2.4 **Aiming**

The aiming sub-test required 75 consecutive aiming movements through repetition of 15 star shape, each star shape comprised of five, aiming movements. The task required was to target dots on the tablet's screen, which eventually form a star shape. This task does not include any guideline. Participants were instructed that once the sub-test started, they should not lift the stylus off the screen. The sub-test was started by placing their stylus on the start position (a circle with the letter ‘S’ within it), prompting a target-dot which was 5 mm in diameter to appear at location 1 see Figure 5-1b. Participants were asked to respond as quickly and accurately as possible to this presentation by sliding their stylus across. Once they reached the target dot the dot disappeared and a new target-dot concurrently appeared at location 2. Participants had to respond to this second target in the same manner as the first, in turn causing it to disappear and the next target-dot to appear at location 3. Participants repeated this pattern of response until the 75$^{th}$ target, after which the finish position (a circle with the letter ‘F’ within it) appeared on screen see Figure 5-1b.

### 5.2.5 **Tracing**

The Tracing sub-test included six trials. In each trial the participant was required to place their stylus on the start position on an otherwise blank screen. After one second, a 4 mm-wide tracing path appeared, connecting the start position to a finish position marked at the other end of the path see Figure 5-1c

The participants were instructed not to lift the stylus off the screen at any point, to move the stylus along the tracing path to the finish position and trying their best to stay within the path's guide-lines whilst doing this. Once they started moving down the path the stylus produced an on-screen ‘ink trail’ (like a real pen), providing feedback to participants on their progress. Each trial demonstrated either path A or B, which had identical geometry but were mirrored vertically see Figure 5-1c.

Paths A and B were presented alternately, meaning each was traced three times. In each trial, a black transparent box appeared on the screen next to the start position surrounding approximately one seventh of the length of the tracing path. After the participant had begun tracing, this box shifted sequentially along the path every 5 seconds and the box would have a total of seven shifts (totalling 35 seconds) by the time it reached the finish position. While Participants were tracing along the path they were clearly instructed to try to remain within this box with their stylus. The presence of this ‘pacing’ box was for the purpose to standardise the speed (approximately), to prevent participants' prioritisation of ‘speed’ and ‘accuracy’ with respect to their performance from confounding results.

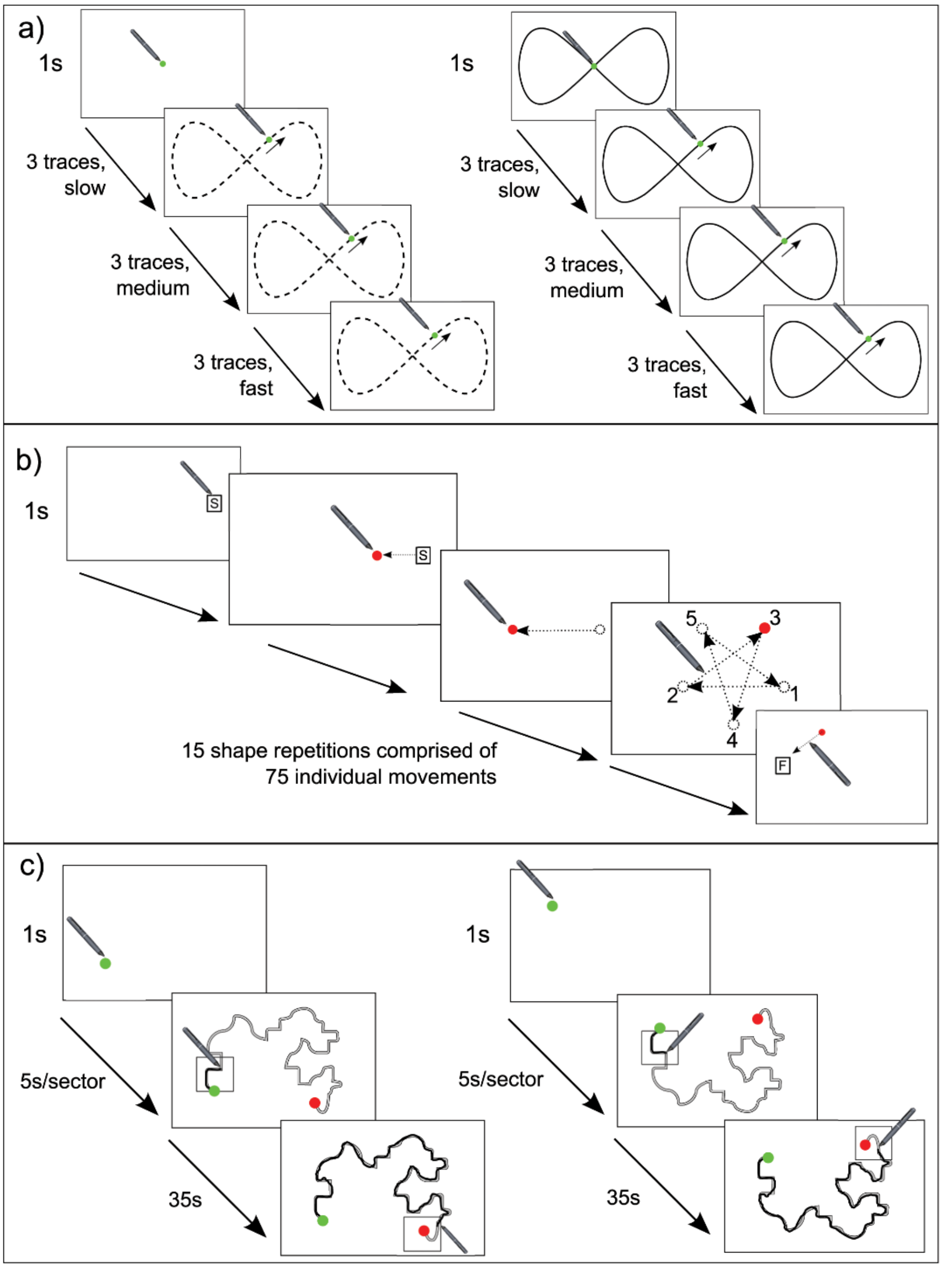


**Figure 5-1** Demonstration of the three manual control battery tasks  Reproduced from Flatters et al (2014) under the Creative Common License. (a) Schematic of Tracking trial, the left Tracking trial is without guidelines, the right included the additional guidelines. (b) Schematic of the Aiming subtest, annotated with dotted arrows implying the movements participants would make with their stylus to move off the start position, between target locations and to reach the finish position. On the 4th panel further annotations indicate the locations in which targets sequentially appeared, with numbers indicating the sequence in which they were cued. (c) Schematic of Tracing, Left is a schematic depicting tracing path A and right is a schematic depicting tracing path B. The black shaky lines are an example of the 'ink trails' a participant would produce with their stylus in the course of tracing.

### 5.2.6 **Procedure**

This experiment involved two phases of data collection**.** The first session was conducted at the Multiple-Mini-Interviews at the school of Dentistry, University of Leeds. The KAT was one of the stations and it was used to assess motor performance in dental students. The second session was conducted when the students reached their 5$^{th}$ year of the dental programme. The students were then invited to take part in the experiment and their participation in the experiment was entirely voluntary. Participating students were made aware of what the study involved and their right to withdraw at any time they wished to do so. Prior to completing the KAT, participants were asked to complete a consent form.

At both time points, students were provided with the instruction sheet followed by verbal instructions on how to perform three tasks. A tablet computer in landscape orientation was placed in front of them with its screen folded flat. The edge of the tablet nearest the participant was 15 cm from the table's edge. Participants were instructed to hold the stylus in their dominant hand and were explicitly asked not to switch the stylus between hands or lift it during testing or use both hands to bimanually manipulate the stylus. They were instructed to, as much as possible, keep their non-dominant hand stationary, on the table top, off to the side of where the tablet had been placed.

Students were then given an opportunity to ask any questions before they started the practise trials. Once the students finished the practise trial, they were then asked to start the testing. The task lasted around 12 minutes and performance was measured on speed and accuracy of the movement as detailed in the data analysis section reported next.

### 5.2.7 **Data analysis**

Scores on each KAT sub-test were generated and matched across the two sessions and then anonymised for analysis.

The Tracking task performance by the participants was measured through the Root mean square error (RMSE), which is a measure of the spatio-temporal accuracy of the participants. The RMSE for each Tracking trial with or without guidelines was calculated with respect to each speed condition slow, medium and fast.

The Aiming task performance by participants was measured through the Movement time (MT) which is the time between arrival at one target location and arrival at the next one in seconds.

The Tracing task performance by participants was measured through path accuracy (PA) which represents the arithmetic mean (in mm) across all samples within each trial for the distance from the stylus to an idealised reference path (path A or B).

The scores on each assessment tracking, aiming and tracing for Year 0 and Year 5 were then calculated, based on each performance metric. Each assessment score from year 0 and year 5 were then converted into z-scores. The assessment scores for each year group were then averaged across to give one score. Each year group scores were then rescaled into percentiles.

A paired-sample t-test was used to analyse the results and to determine statistical significance (with an alpha threshold of .05). followed by a Pearson's correlation to examine whether there was a relationship between the variables. Data were analysed using R version 3.3.1.

## 5.3 Results

A paired-sample t test was conducted to compare if student performance at the KAT changed over time (see Figure 5-2). It was found that the difference, 5.54, 95 % CI [-3.60, 14.67], was not statistically significant, t (29) = 1.240, p = 0.225 and represented a small size effect, d = 0.23.

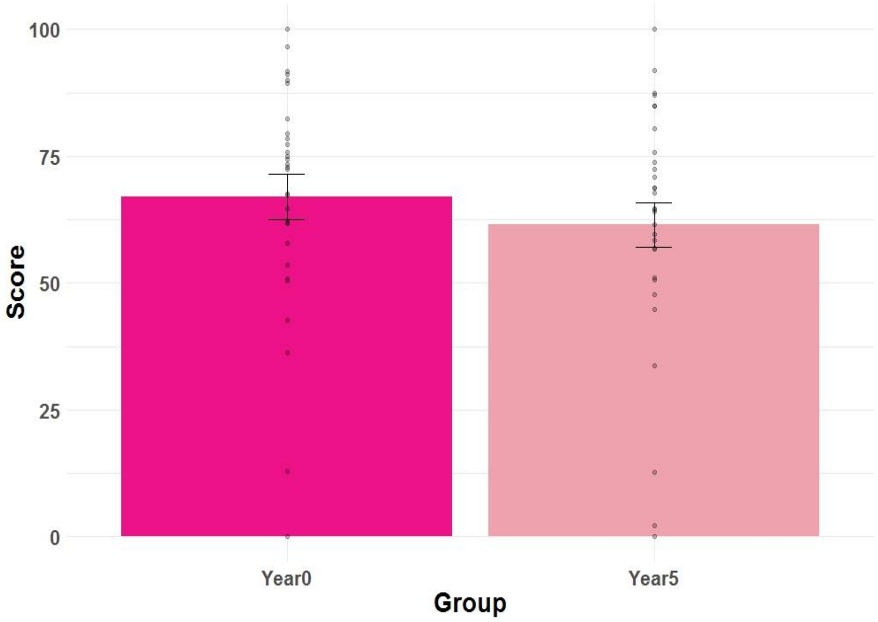


**Figure 5-2** Student performance on the KAT at Year 0 and Year 5 of undergraduate Dental training. Each black circle represents an individual participant and the error bars show standard error of the mean**.**

Next, an important part of the investigation was to examine whether individual participant scores at the two different time points bore any relationship with one another. To this end, a Pearson's correlation was performed and a statistically significant moderate positive correlation was found between the two groups (r = .460, p = 0.011; see Figure 5-3), thus indicating a reliable relationship between assessments at Year 0 and Year 5.

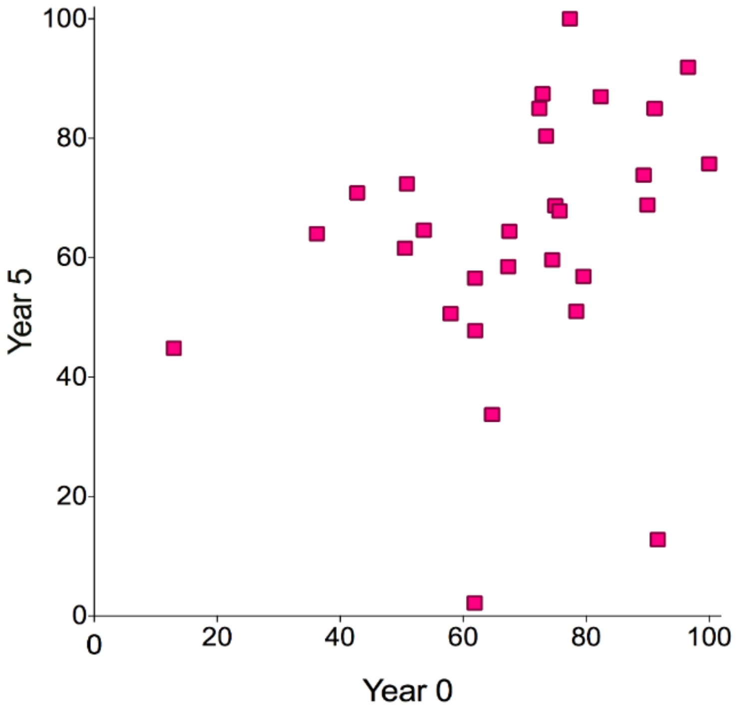


**Figure 5-3**: The correlation between dental students' performance. Scatterplot illustrates there was a positive correlation between dental student performance in year 0 (i.e. at selection) and in year 5 of undergraduate dentistry. One possibility for the outliers presented in the scatterplot was students experiencing technical problems with the KAT.

## 5.4 Discussion

There have been a few studies exploring the test-retest validity of manual dexterity tests designed to measure the sensorimotor abilities of dental students.

Here, we examined whether there would be any performance differences on a manual dexterity test conducted during the interview selection stage and five years into dental education. The results showed no statistically reliable change in dental student motor performance.

The majority of studies that have examined changes in manual dexterity over time have commented on the value of these tools as continual assessment devices rather than use as initial screening tools (Gansky et al., 2004; Giuliani et al., 2007; Luck et al., 2000). However, the present data offer an alternative take- suggesting that the kinematic assessment tool provides a stable and reliable measure of performance over a long period of time. Thus, there seems to be an opportunity to use such a device as a screening tool at the outset of training.

It is worth comparing this study’s results with other studies reporting that manual dexterity can be educated and improved over time provided the ‘correct’ training is received (Gilad Ben-Gal et al., 2017; Giuliani et al., 2007; Luck et al., 2000). However, it is important to note that the majority of tasks used to examine sensorimotor performance in previous work have not been “pure” measures of sensorimotor capability – often involving cognitive elements that can be improved through repetition or have some applied relevance to dental training and thus have the potential to be ‘contaminated’ by knowledge acquired during dental training. Here, I implemented a task that was designed to capture the fundamental characteristics of sensorimotor performance outside of any dentistry specific training and with minimal cognitive demands.

The findings are particularly compelling given that there are other factors that could have contributed to observing differences in these data. This study used the KAT results recorded at the MMI's year 0 and the KAT in year 5. Inevitably, the stakes of an individual performance were much higher at the interview stage as they were being assessed and competing against each other- and this motivator would be expected to impact on performance (Kirby, 1979). In contrast, in year 5, participants took part on a voluntary basis and there were no consequences of poor performance on educational outcomes.

We also note that the ability to recruit participants was impacted by the study timeframe- which coincided close to the fifth-year final exams and busy scheduled university activity/timetables which involved the dental students to be out of campus. A longer timeframe would have led to more participation which in turn a larger sample size would have improved the reliability of this study. However, it is worth noting that even with a relatively small sample, there was a significant moderate positive correlation between the performance of the KAT at the MMI's year 0 and in year 5.

For future work, it would be useful to compare dental performance of the students after completing their preclinical training and across different cohorts.

## 5.5 Conclusion

There was no change in the dental students' motor performance in KAT over time. However, a significant moderate positive correlation was found between the KAT scores at the interview process and at the year 5 indicating its potential usefulness as an assessment tool in the selection process. In the next chapter we examine the relationship between performance on the KAT and dental educational performance.

# Chapter 6 MMIs as a Predictor of Undergraduate Dental Performance

## 6.1 Introduction

Face-to-face interviews to assess prospective applicants were the norm for both medical (Anderson, Hughes, & Wakeford, 1980; Fruen, 1980; Litton-Hawes, MacLean, & Hines, 1976) and dental schools (Killip, Fuller, & Kerber, 1979; Walker, Killip, & Fuller, 1985) for a long period of time. Whilst these approaches have strong face validity (i.e. the subjective assessment of whether a test measures or captures the construct that it purports to index; Morris, 1999)), they have shown poor predictive value, failure to capture the wide-ranging number of skills required for dentistry and potential for interviewer and social bias. These factors have led to many dental institutions seeking alternative methods (Albanese, Snow, Skochelak, Huggett, & Farrell, 2003; Kreiter et al., 2004; Mann, 1979; Razack et al., 2009; G. D. Roberts & Porter, 1989) for assessing prospective applicants.

In a previous chapter in this thesis, we described a common approach adopted by many dental schools across the world today (Alaki, Yamany, et al., 2016; Brownell, Lockyer, Collin, & Lemay, 2007; Dowell et al., 2012; C. Roberts et al., 2008, 2009) - the multiple mini interview (MMI) format. Briefly, MMI's use short independent assessments, typically in timed circuits designed to resemble the Objective Structured Clinical Examination (OSCE) rated by one or two assessors.

In general, applicants and interviewers have reported MMIs to be positive (Barbour & Sandy, 2014; McAndrew & Ellis, 2012, 2013). However, a thematic analysis of student feedback reported a number of emergent theme such as lack of control, anxiety, nervousness, comparisons and preparedness (McAndrew & Ellis, 2012, 2013). In terms of reliability, the intra-station reliability (the internal consistency for each station), inter-item reliability (the internal consistency of the scores assigned within any one station) and the inter-rater reliability (interviewers giving similar scores to similar interview performance) within MMI stations range from moderate to high (Dore et al., 2010; Lemay et al., 2007; Pau et al., 2013; C. Roberts et al., 2008).

Recent work has examined the relationship between performance on the MMIs, alternative admission measures such as the UKCAT and high school GPA scores and examined whether they have any power to predict academic performance (Alaki, Yamany, et al., 2016; Foley & Hijazi, 2013; Husbands & Dowell, 2013; McAndrew et al., 2017) For example, one study investigated the correlation between interview scores in two universities (Cardiff - which uses multiple mini interviews, and Newcastle - which uses semi structured interviews) with subsequent examination scores. The results showed that there was no correlation between examination scores and interview scores (MMI and traditional interviews) in either university. However, the UKCAT was linked to poor academic performance in primary Bachelor Dental Surgery part 1 which is the summative examination results for anatomy, physiology and biochemistry ($P=0.06$) and primary Bachelor Dental Surgery part 2 which is the summative examination results for oral ecosystems and clinical dentistry ($P=0.03$) in Cardiff, and a borderline fail at Newcastle ($P=0.001$) (McAndrew, Ellis and Valentine, 2017).

Another study showed a positive correlation between MMI scores and GPA performance in Year 1 and Year 2 of dental training (Alaki, Yamany, et al., 2016). Specifically, these researchers found a significant positive relationship between a global MMI score and semester GPA ($r = .434$, $p <.0001$) and cumulative GPA ($r =0.424$, $p < 0.0001$) in Year 1. This relationship persisted in the second year for both semester's GPA ($r = 0.411$, $p <0.0001$) and cumulative GPA ($r = 0.393$, $p< 0.001$). Similarly, Foley & Hijazi (2013) found a correlation between performance at the MMIs and Common Assessment Score (CAS), a performance measure which took into consideration scores of all end of term and end of year examinations ($r = 0.180$, $p = 0.001$, $df = 538$). Interestingly however, pre-admission scores ($r = 0.050$, $p = 0.248$, $df = 538$) and Universities and Colleges Admissions Services UCAS scores ($r = -0.059$, $p = 0.169$, $df = 538$) did not correlate with the CAS.

In a previous chapter, we examined the MMIs employed at the University of Leeds and showed that this interview process captured two fundamental traits across ten assessment stations - soft skills and visuomotor skills. Building on this work, in this study we will use these results as a platform from which we will conduct an exploratory analysis which will investigate the predictive validity of these specific traits on academic performance that was designed to assess such abilities. For completeness all intra year (and intra-module/assessment) performance will be included in the data analysis section of this chapter.

The majority of studies in dentistry examining this topic have focussed on the ability of the MMIs to predict overall academic or examination performance and have been retrospective in nature. The following study adopted a longitudinal approach, providing more detailed examination into the ability of each construct measured by the MMIs in predicting soft skills and motor performance (in pre-clinical and clinical settings) across the curriculum.

The aim of this study was to examine the predictive relationship between performance on MMI stations in the School of Dentistry and the undergraduate dental student performance over the dental degree. Our specific objectives were to explore the relationship between students' MMI performance (visuo-motor stations and soft skills stations) and their subsequent performance in selected motor and soft skills tasks.

## 6.2 Material and methods

### 6.2.1 Participants

A self-selecting sample of the 2014-2015 Dental Surgery programme's cohort of undergraduate students (N= 60, 47 females,13 males) were recruited from the School of Dentistry, University of Leeds. This was an opt out study, so any student who wished to withdraw simply clicked on a link and their data were removed. All data collected from students were anonymised and were identifiable by a unique participant identification number (UPN) to protect student identity and to further secure anonymity individual UPNs were replaced with a subject ID. Ethical approval was gained by Dentistry Research Ethics Committee (DREC) at the University of Leeds and the School of Psychology (DREC ref: 271016/IM/216).

### 6.2.2 The Dental Curriculum Measures

The Dental curriculum at the University of Leeds consists of 24 modules. There are six modules for year 1 (Professional Development 1, Health Promotion, Oral Environment, Oral Disease, Pain Management and Clinical Practice1), 5 modules for year 2 (Clinical Skills A, Social Sciences, Biomedical Sciences, Professional Development 2, Clinical Practice 2), 6 modules for year 3 (Illness & Wellbeing, Undergraduate Project, Clinical Skills B, Child Dentistry, Professional development 3, Clinical Practice 3) and 6 modules for year 4 (Clinical Sciences, Adult Dentistry, Child Dentistry Clinical Practice 4, Professional Development 4 and the first part of the 'Final Year' Project.

A total of 23 modules taught up to the fourth year of dentistry were correlated with scores obtained on the MMIs in this chapter. Year 5 data were not included in this study since their examinations results would appear after the submission of this thesis. For assessment details for each module please see Appendix B2.

In addition to these global module marks, we also selected extracted measures on tasks from across the dental curriculum most closely mapped to the skills assessed at interview (i.e. soft skills and visuomotor skills). We describe the extracted measures next.

### 6.2.3 Selected Soft Skills Tasks

From each year group a “soft skill” assessment task was selected from a module formal assessment (see Figure 6-1). We note that whilst these assessments often involved elements beyond soft skills (e.g. OSCEs are designed to capture more than soft skills and relate to specific knowledge), they involved elements that provided the closest approximate mapping with the skills assessed at the MMIs.

The six assessment soft skills tasks included Group work presentation from year 1 (which accounts for 25% of the Personal and Professional Development 1 module formal assessment) and Poster presentation from year 2 (accounting for 60% of the Personal and Professional Development 2 module formal assessment).

Scores from Year 3 included OSCE performance (which accounted for 40% of the Clinical Practice 3 module formal assessment) and a presentation (which accounted for 40% of the Personal and Professional Development 3 module formal assessment).

For Year 4, we included OSCE performance on the Clinical Practice 4 module formal assessment and a presentation (which accounts for 10% of the

Personal and Professional Development 4 module formal assessment). See Appendix B2 for more details of the soft skills tasks used for analysis.

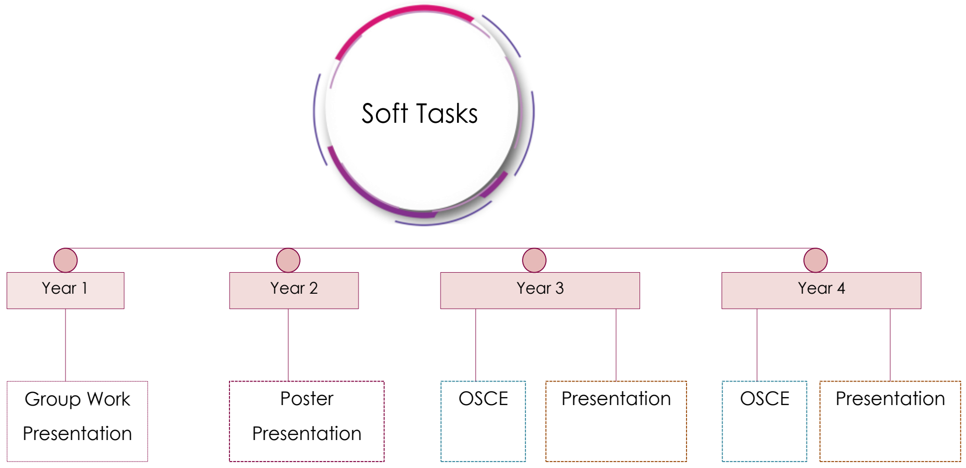


**Figure 6-1** The six tasks extracted from each year group with the closest mapping to the soft skills assessed during the MMIs.

## Selected motor skills tasks

From each year group a motor skill assessment task was selected from a formal module assessment (see Figure 6-2). The seven motor tasks included: (i) the Simodont induction - Year 1, (ii) a Spotter test - Year 2, (iii) a Pre-clinical crown test - Year 3; and (iv) OSCE - Year 3 (v) a Clinical crown test Year 4 (vi) a Spotter test Year 4 (vii) OSCE Year 4. The OSCE tasks assessed in the Soft Skills analysis was included as these tasks involve elements of soft and motor skills.

The Virtual Reality Haptic dental simulator (Simodont) induction performance from year 1 (the results of student practice trials on the manual dexterity exercise available in the Simodont courseware) were downloaded from the Simodont server, filtered, arranged in excel sheets, calculated and exported to SPSS for analysis. We standardised the selection criteria as follows: the minimum task completion level 60% and container damage equals zero. The average best attempts for each student were calculated (Score = target – ((Leeway Sides + Leeway Base)/2)).

The Year 2 Spotter test accounts for 50% of the Clinical Skills A module formal assessment. It is 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 their performance.

The Year 3 Preclinical crown test accounts for 50% of the clinical skills B module formal assessment. It involves a 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 work e.g. identification of preparation errors).

Year 3 OSCE It accounts for 40% of the Clinical Practice 3 module formal assessment.

Year 4 Spotter test accounts for 50% of the Complex Adult Dentistry module formal assessment. The test required the students to identify problems and how to rectify them from topics taught in this module (e.g. denture model on an articulator and having to identify problems such as wrong or defective restoration or preparation). The dental instructor then assigned a mark out of 100 based on their performance.

The Year 4 OSCE accounts for 50% of the Clinical Practice 4 module formal assessment. The Year 4 Clinical crown test is a progressional assessment test which is part of the Clinical practice 4 module formal assessment. Each student was assigned a pass or fail. Details of the assessment scores were gained through the Operative department. This test involves a clinical crown preparation on real patients.

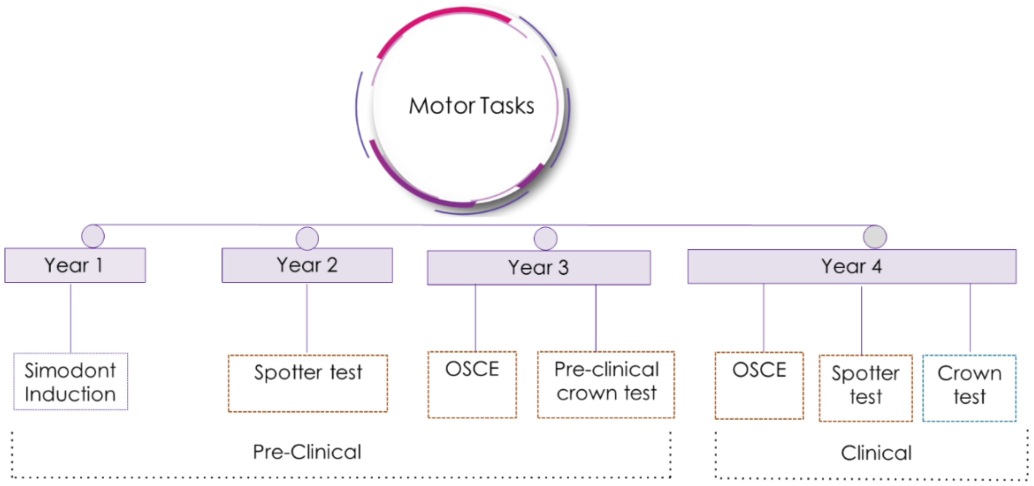


**Figure 6-2** The 7 tasks extracted from each year group with the closest mapping to the visuomotor skills assessed during the MMIs

## Data Analysis

The result of the factor analysis from the previous study for the MMI stations revealed two factors that explained the underlying structure of the MMIs (which were the soft skills and the visuomotor skills). The first factor which represented the soft skills had six stations associated with it (presentation, memory, ethics, interpretation and insight). The second factor which represented the visuomotor skills had four stations associated with it (origami, simulator performance - Simodont, CKAT, and Tangram). For statistical analysis, a “soft skills” score and a “visuomotor score” was calculated for each student based on the loading strength of each station to the factor.

A correlation matrix with Pearson’s correlation coefficient was computed to assess the relationship between the dental student performance in the MMI on visuomotor and soft skills and module performances across the dental training programme (from Year 1 up to year 4) and specifically in the selected motor and soft skills task performance measures.

Given the focus of this chapter, the analysis and reporting will focus only on relationships between the MMIs and our extracted performance measures. For completeness, all intra year (and intra-module/assessment) correlations are presented on the heatmaps. The heat map introduced in the result section will show the degree of correlation of the MMI station score (soft skills/visuomotor score) to the modules/task performance. The task performance will include soft skills and motor skills tasks. A significant correlation will be marked in orange while a no significant correlation will be marked white. All data were analysed using R version 3.3.1.

## 6.3 Results

### 6.3.1 MMI soft skills stations and module performance

A Pearson's correlation coefficient was computed to assess the relationship between the MMI soft skills stations and module performance. A significant positive correlation was found between the MMI soft skills stations and 12 modules across the four-year dental programme. This indicates that as the students' performance in the MMI soft skills stations increased, performances in the modules also increased. Those modules included: Oral disease (r =.35, p=.039, df=51), Oral environment (r = .30, p=.031, df = 51) and Clinical Practice (r = .20, p = .039, df = 51) from year 1. From year 2, Clinical Skills A (r = .22, p = .029, df = 51), Social sciences (r = .45, p <.001 df=51) and Biomedical Sciences (r =.35, p = .021, df = 51). From year 3, Professional Development (r = .28, p = .018, df = 51), Clinical Practice (r =.62, p < .001, df = 51) and Clinical Skills B (r = .28, p = .011, df = 51). From year 4, Clinical Practice (r = .51, p < .001, df = 51), Complex Adult Dentistry (r = .42, p = .001, df = 51) and Child-Centred Dentistry 2 (r = .30, p = .007, df = 51) see Figure 6-3 below.

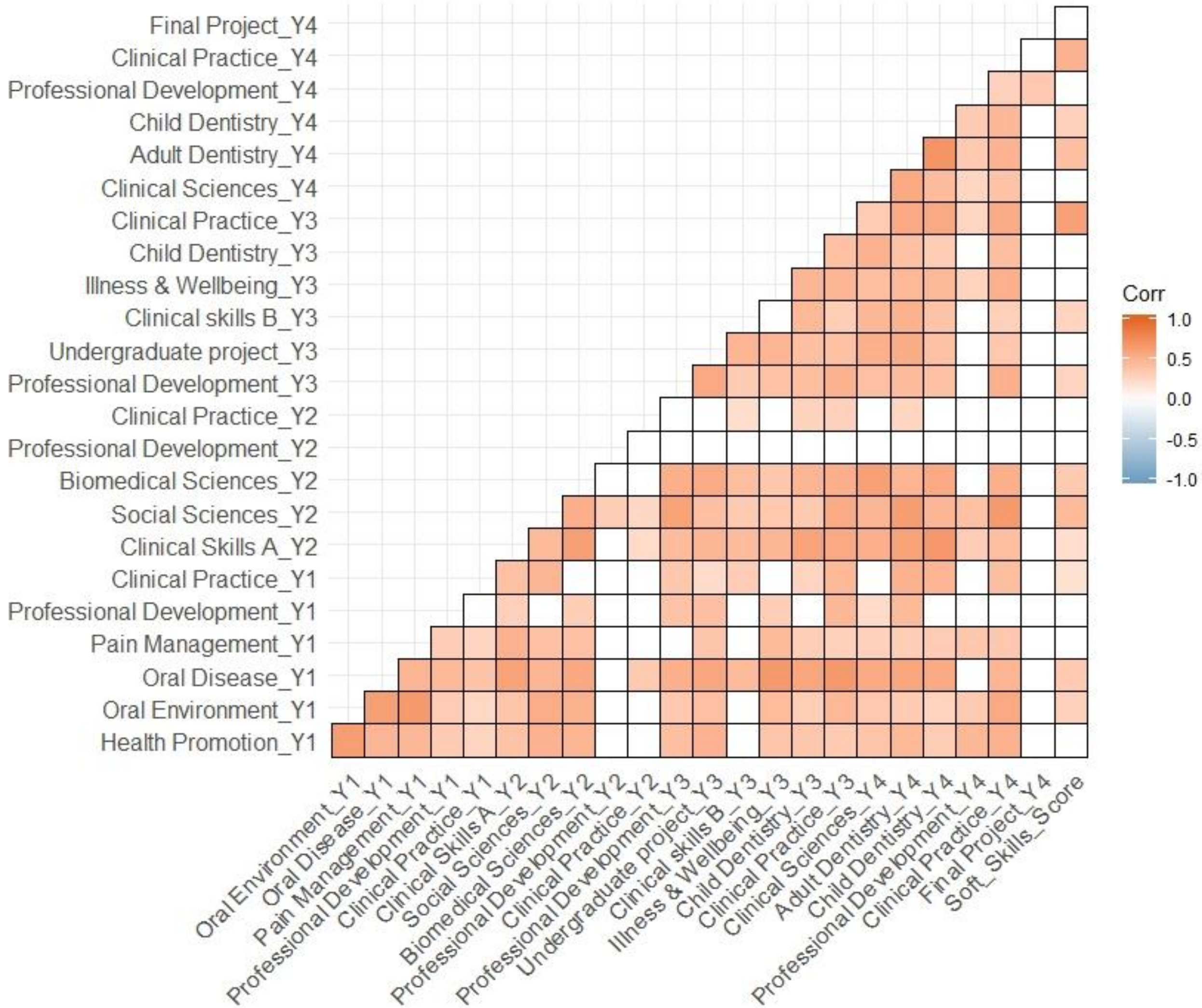


**Figure 6-3** Heatmap plot for MMI soft skills stations and module performances. The heatmap shows the degree of correlation of the soft skills stations to the modules, significant correlation between the soft skills stations and the modules is marked in orange, no significant correlation is marked as white.

### 6.3.2 MMI Soft Skills Stations and Selected Soft Skills Tasks

There was a significant positive correlation between the MMI soft skills stations and OSCE year 3 ($r = .57$, $p = .028$, df =52) and OSCE year 4 ($r =.52$, $p = .050$, df =52). However, no correlation was found between MMI soft skills stations and Group presentations year 1, Poster presentation year 2, presentation year 3 and presentation year 4 Figure 6-4.

From the MMI soft skills stations, the stations that had a significant positive correlation with OSCE year 3 scores were the Communication station ($r =.48$, $p <.001$, df =52), the Interpretation station ($r = .49$, $p = .002$ df = 52) and the presentation station ($r = .36$, $p = .005$, df = 52). The Year 4 OSCE scores had a significant positive correlation to the Insight station ($r = .48$, $p = .003$, df = 52) and the Communication station ($r =.48$, $p < .001$, df = 52) and interpretation station ($r = .40$, $p = .008$, df = 52; see Figure 6-5). There was also a significant correlation between the Communication station and Ethics ($r= .31$, $p = .030$, df = 52) and Memory scores ($r= .39$, $p = .016$, df = 52).

Details of the MMI soft skills stations and the soft skills tasks correlation are reported next. There was no statistically significant correlation between students' performance at the MMI soft skills stations and the group work presentation in Year 1 ($r = -.09$, $p = .341$, df = 52). There was also no statistically significant correlation between students' performance at the MMI soft skills stations and poster presentation scores in Year 2 ($r = .00$, $p = .789$, df = 52). Similarly, there was no statistically significant correlation between students' performance at the MMI soft skills stations and the presentation year 3 ($r = -.11$, $p = .239$, df = 52). Nor was there a statistically significant correlation between students' performance at the MMI soft skills stations and poster presentation scores in year 4 ($r = .05$, $p = .607$, df = 52).

We did however, observe a significant positive correlation between students' performance at the MMI soft skills station and the OSCE year 3 ($r = .57$, $p = .028$, $df = 52$) and OSCE scores in year 4 ($r = .52$, $p = .050$, $df = 52$).

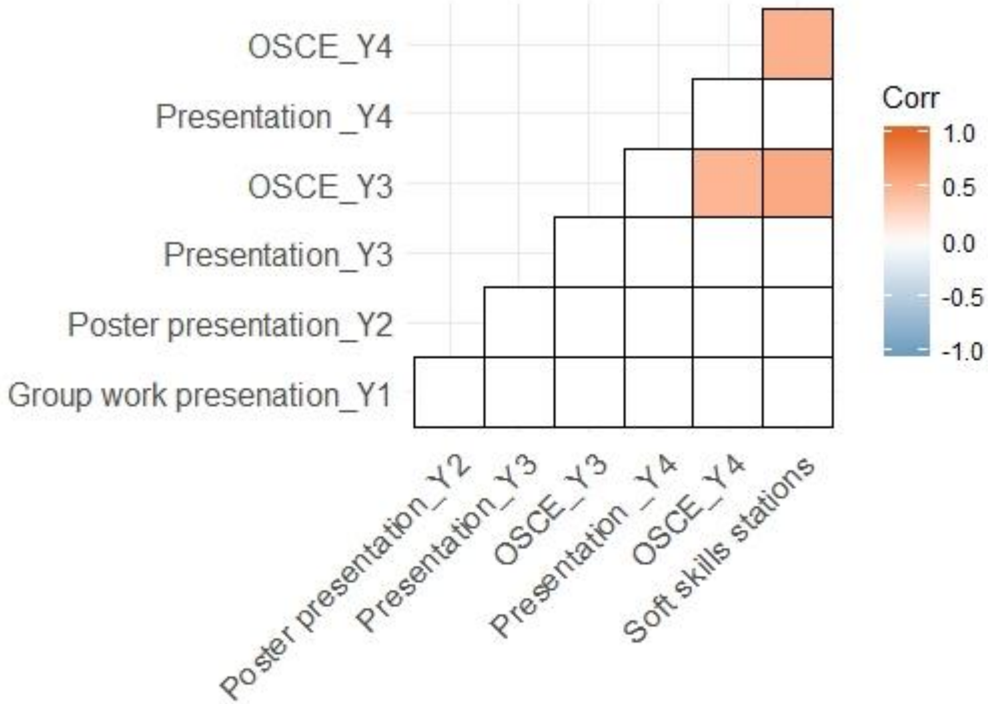


**Figure 6-4** Heatmap plot for MMI soft skills stations and soft skills tasks performance. The heatmap plot shows the degree of correlation of the soft skills stations to the soft skills tasks, significant correlation between the soft skills stations and the soft skills tasks is marked in orange, no significant correlation is marked as white.

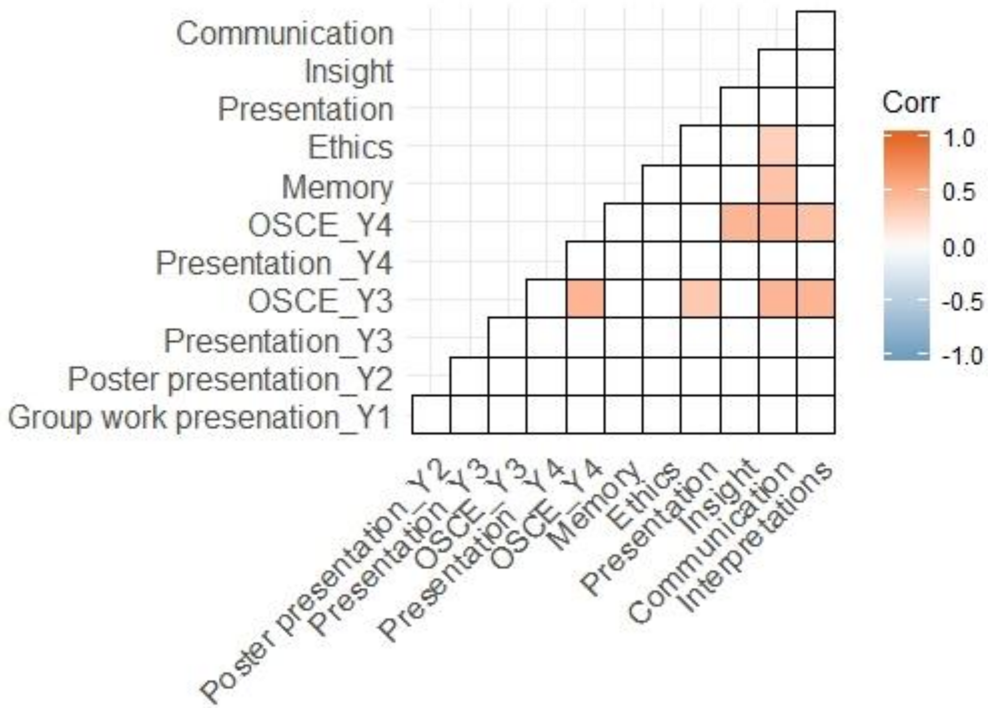


**Figure 6-5** Heatmap plot for each individual MMI soft skill station and soft skills tasks performance. The heatmap plot shows the degree of correlation of each soft skill station to the soft skills tasks, significant correlation between each soft skill station and the soft skills tasks is marked in orange, no significant correlation is marked as white.

### 6.3.3 **MMI visuomotor stations and module performance**

Unlike the soft skills stations the MMI visuomotor stations only correlated with one module across the dental module programme, with a significant positive correlation between the MMI visuomotor stations and the health promotion Module in Year 1 ($r = .33$, $df = 51$, $p = .012$) see Figure 6-6

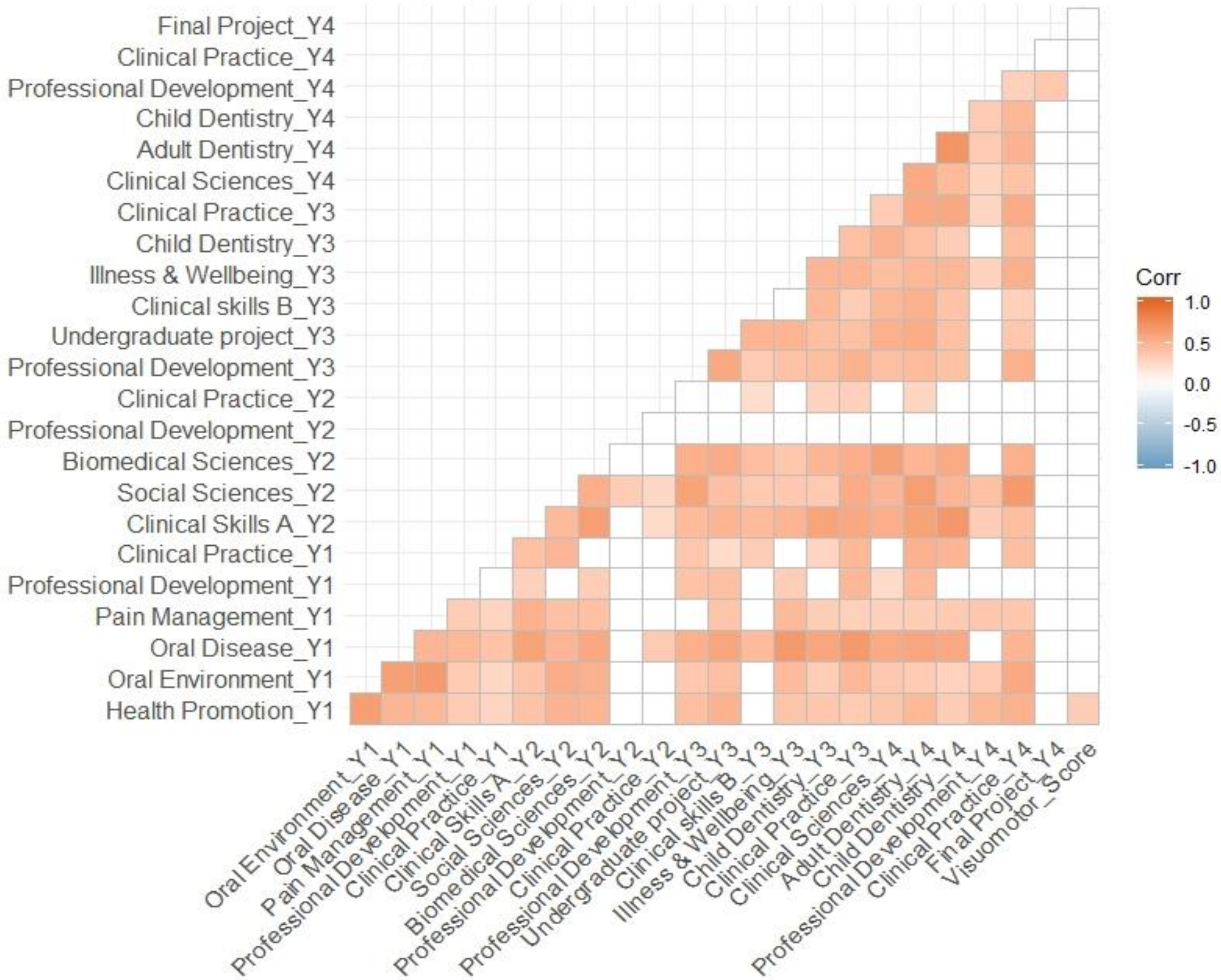


**Figure 6-6** Heatmap plot for MMI visuomotor skills stations and module performances. The heatmap plot shows the degree of correlation of the visuomotor skills stations to the modules, significant correlation between the visuomotor skills stations and the modules is marked in orange no significant correlation is marked as white.

### 6.3.4 MMI visuomotor stations and selected motor tasks

A correlation analysis between the MMI visuomotor stations and the selected motor tasks were performed. The motor tasks included Simodont induction from year 1, Spotter test from year 2, Pre-clinical crown test from year 3, Spotter test from year 4, Clinical crown test year 4.

No significant correlation was found between students' performance in the MMI visuomotor stations and these five motor tasks. However, a significant positive correlation was found between the Spotter test from year 2 and the Spotter test from year 4 ($r = .32$, $p = .005$, $df = 45$) indicating that as the students' performance increased on Spotter test year 2 it also increased in Spotter test year 4. Similarly, the Clinical crown test from year 4 had a significant correlation with Pre-clinical crown test from year 3 ($r = .19$, $p = .023$, $df = 45$) and spotter test year 4 ($r = .28$, $p = .037$, $df = 45$), see Figure 6-7.

Of the MMI visuomotor stations, although none of the visuomotor stations had a significant correlation with the motor tasks, the Simodont station and the Origami station had positive correlations compared to the Tangram station and CKAT station see Figure 6-8. Details of the MMI visuomotor stations and motor tasks correlation are reported next.

There was no significant correlation between the students' performance in the MMI visuomotor stations and the Simodont induction data year 1 ($r = .15$, $p = .972$, $df = 45$). There was also no significant correlation between students' performance in the MMI visuomotor stations and Spotter test year 2 ($r = .02$, $p = .549$, $df = 45$). Similarly, we found no relationship between students' performance in the MMI visuomotor stations and Pre-clinical crown test year 3 (r

= -.06, p = .700, df = 45) or the Spotter test in Year 4 (r = .23, p = .208, df = 45) or the Clinical crown test in Year 4 (r = .08, p = .484, df = 45).

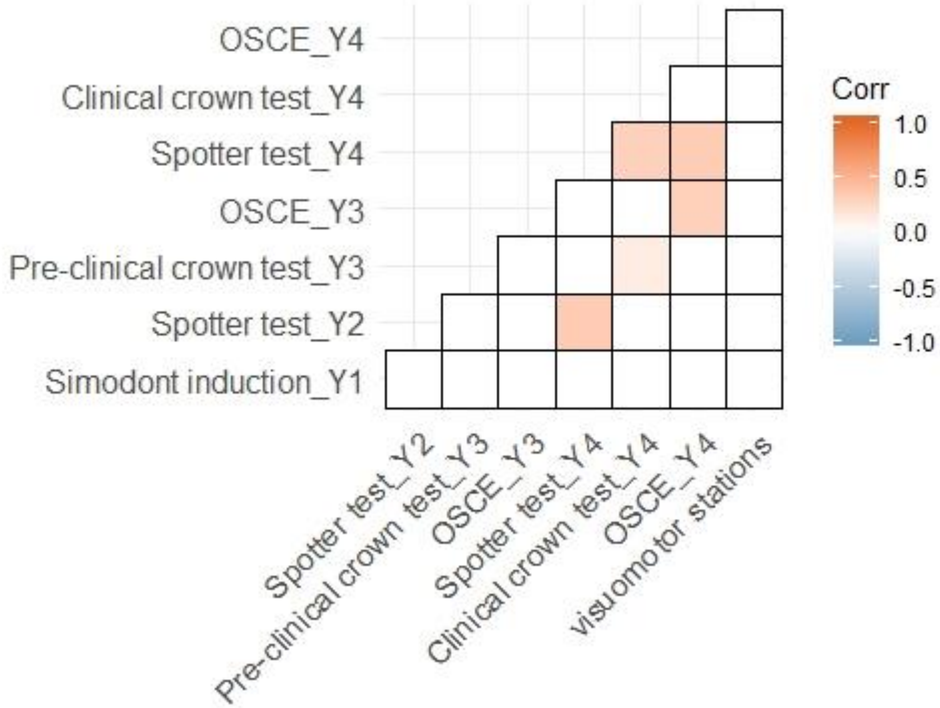


**Figure 6-7** Heatmap plot for MMI visuomotor skills stations and motor skills tasks performance. The heatmap plot shows the degree of correlation of the visuomotor skills stations to the motor skills tasks, significant correlation between the visuomotor skills stations and the motor skills tasks is marked in orange, no significant correlation is marked as white

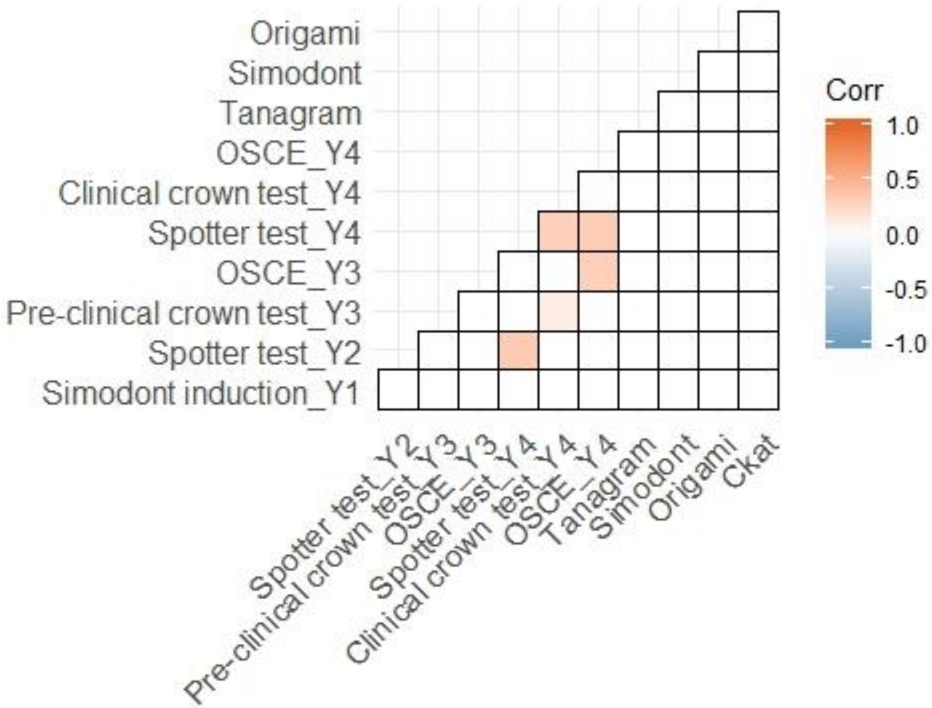


**Figure 6-8** Heatmap plot for each individual MMI visuomotor skill station and motor skills tasks performance. The heatmap plot shows the correlation between each individual visuomotor station and motor task performances, significant correlations between each individual visuomotor station and motor task performances is marked in orange, no significant correlation is marked in white

## 6.4 Discussion

Today, MMIs are seen as a reliable and reputable admission tool to assess non-cognitive attributes in the medical field (Knorr & Hissbach, 2014) and are increasingly used for dentistry (Dowell et al., 2012; McAndrew & Ellis, 2012). However, there have only been a few studies reporting the validity of this assessment approach for predicting subsequent academic success and these studies have generated mixed results. For example while some studies have showed positive finding between the MMI scores and examination scores (Alaki, Shinawi, et al., 2016; Alaki, Yamany, et al., 2016; Foley & Hijazi, 2013), others have reported no correlation between examination scores and MMI performance (McAndrew, Ellis and Valentine, 2017). These previous approaches have also only focussed on general academic performance measures (e.g. overall module or semester grade). Here, we set out to perform a detailed examination between performance on the MMIs and specific, as well as general, performance across the undergraduate dental training programme at the University of Leeds. We specifically focussed on the relationship between visuomotor and soft skills, as assessed in the MMI and mapped this to relevant assessments across the course.

The results showed that the MMI soft skills scores correlated with some of the dental modules but, in contrast, the MMI visuomotor scores correlated to only one dental module. Similarly, the MMI soft skills scores correlated with some of the soft skills tasks, but the MMI visuomotor skills scores did not correlate to any of the motor specific tasks in the dental modules.

Surprisingly, the MMI soft skills scores (Memory, Ethics, Presentation, Insight, Communication and Interpretations station scores) were able to predict 12 out of 24 assessment modules. The modules predicted included 3 modules out of 6 modules from year 1 (Oral Environment, Oral Disease and Clinical practice 1), 3 modules out of 5 modules from year 2 (Social Sciences, Biomedical Science and Clinical skills A), 3 modules out of 6 modules from year 3 (Professional and Development 3, Clinical skills B and Clinical Practice 3) and 3 modules out of 6 modules from year 4 (Adult Dentistry, Child Dentistry and Clinical Practice 4). This is a highly promising result - showing how assessments at MMI map on to relevant training across the dental training programme. Similar positive findings have been reported between MMI scores and academic examination scores, however, these studies included GPA performance score up to year 1 (Alaki, Shinawi, et al., 2016; Foley & Hijazi, 2013) or year 2 only (Alaki, Yamany, et al., 2016).

In our secondary analysis, exploring the relationship with selected soft skill tasks from across the dental programme (i.e. Group work presentation year 1, Poster presentation year 2, Presentation year 3, OSCE year 3, Presentation year 4 and OSCE year 4) we found that the MMI soft skills scores correlated with 2 the OSCE in year 3 (which had a significant correlation with the communication, presentation and the interpretation station) and the OSCE year 4 (which had a significant correlation with the insight, interpretation and the communication station). Notable is the overlap between the communication and the interpretation stations and OSCE performances in year 3 and 4. This observed relationship between soft skills stations and OSCE performance could be driven by the presence of core skills that are needed by the dental students in order to perform well in the OSCE which, in part, requires students to communicate with patients effectively, showing empathy and sympathy and engaging with the patient (ADEA House of Delegates, 2011; Cowpe et al., 2010). This pattern of results is in alignment with one study where MMI stations, in particular the stations which assessed critical thinking, professionalism, presentation and communication skills were able to predict academic achievements and specifically performance-based subjects (Lee et al., 2016).

In contrast to the soft skills results, the MMI visuomotor scores (CKAT, Tanagram, Simodont and Origami) correlated with only one module score- the Year 1 health promotion module. There was no a prior expectation for this mapping, and we must note that given the number of correlation tests performed here, this result may have occurred just by chance and could be treated as a false positive. With this caveat, it is worth noting that part of this course includes cardiopulmonary resuscitation, which requires a degree of motor performance along with clinical reasoning which is required in performing a dental procedure and thus some of the variance in this score may be captured by the visuomotor score from the MMI.

While our focus was on MMI scores, we also noted a significant correlation between clinical and the pre-clinical crown tests. This finding is consistent with Velaya et al (Velayo, Stark, Eisen, & Kugel, 2014) who reported that preclinical training on phantom head with mounted plastic teeth is associated with subsequent clinical performance. In contrast, reports from other studies have shown no correlation between preclinical training on typodont and subsequent clinical performance (Curtis, Lind, Brear, & Finzen, 2007; Nunez, Taleghani, Wathen, & Abdellatif, 2012).

We also found a significant correlation between the spotter tests in Years 3 and 4, suggesting that the two tests are capturing the same underlying traits. Importantly, these two tests differ from the other motor tasks in the fact that these spotter tests are designed to assess the cognitive ability of students to identify critical preparation and restoration errors rather than their fine motor skills per se.

Unlike the CKAT and Tangram, which showed no correlation with the motor tasks, the Simodont and Origami showed weak positive correlations. These particular findings are contrary to previous work reporting a positive association between student performance on haptic simulators assessment and preclinical (A. Urbankova, 2010; Alice Urbankova et al., 2013; Alice Urbankova & Engebretson, 2011) and clinical performance (L. M. Al-Saud et al., 2019).

However, these differences in the results could be due to the fact that in this study (in contrast to those showing positive findings), the MMI candidates were informed that performance on the Simodont (and indeed, the KAT) would not contribute to their assessment and thus may have impacted on student motivation and performance.

Several authors have proposed that manual dexterity tests are valuable tools in predicting individuals pre-clinical performance (Kothe et al., 2013, 2014; A. Urbankova, 2010; Alice Urbankova et al., 2013; Alice Urbankova & Engebretson, 2011) and a correlation between manual dexterity station and year 1 performance was recently reported (Foley & Hijazi, 2013). However, there is also conflicting evidence showing manual dexterity tests to be poor predictors of pre-clinical performance (Gansky et al., 2004; Giuliani et al., 2007; Luck et al., 2000; Lundergan et al., 2007; Oudshoorn, 2003; Waldman et al., 1995).

The surgical training literature more broadly has grappled with a similar topic in examining the correlation between surgical performance and manual dexterity test scores (Gansky et al., 2004; Giuliani et al., 2007; Luck et al., 2000;

Maan et al., 2012). These studies have highighted that there are a number of factors that can influence performance and manual dexterity such as motivation, individuals' judgement and the training received (Kirby, 1979). In light of these mixed findings, others have stressed the use of manual dexterity tests as tools in monitoring and assessing improvement or detriment in one's manual dexterity over a prolonged period of time (de Andrés et al., 2004; Luck et al., 2000). Given our previous findings (showing a stability in measurement from the KAT), this seems like a useful avenue to explore.

Based on these results, we propose that admissions committees continue to regularly review data obtained from the admissions process to help develop and refine MMIs so that they more closely map on to the demands of undergraduate dentistry. In addition, the various stations and domains that were assessed by the selection process may need to be weighted and where indicated give greater credence to those stations that appear to better predict the module performance. This will help in redeveloping and reassessing these stations and at the same time give us a better understanding of the desirable attributes of the dental profession needed at entry level. In future work, it would be useful to include more data and different cohort to improve the external validity of the study and avoid selection bias. Given the exploratory nature of this study, examining correlations presented a useful starting point for this topic. Longer term, where correlations exist, it would be useful to disentangle relationships in more detail. The analysis was constrained by measures that were made available by the dentistry education team and the ethics approval applied only to a specific cohort. Future work with appropriate permissions would allow us to examine the generalisabilty of these results to other cohorts and larger samples.

## 6.5 Conclusion

The current study suggests that there is an association between admission performance at the MMI soft skills stations and subsequent module performance while the MMI visuomotor stations did not predict module performance.

# Chapter 7 Discussion

## 7.1 Overview

The overarching goal of this thesis was to systematically examine the value of early assessment of skills on predicting subsequent dental performance, including the development of sensorimotor skills and academic performance. Particular emphasis was placed on a Virtual Reality haptic simulator, known as the Simodont, which had recently been implemented in the School of Dentistry at the University of Leeds at the start of this thesis, thus providing a unique opportunity to investigate its utility.

Throughout the thesis, the aim was to ask whether current practices allow us to predict real-world performance in dental students and whether existing admissions tools are adequate for undergraduate dental student selection. These issues were addressed through a series of cross-sectional studies and one longitudinal experiment. These questions can be parsed into three themes: (i) the validity of the virtual reality simulator; (ii) the reliability and validity early assessment of motor and academic aptitude; and finally, (iii) the role of simulation in dental education. A discussion of these themes, informed by the empirical data reported in the preceding chapters, is presented next.

## 7.2 Using Virtual Reality Simulators in Dental Education

VR simulators are thought to provide a virtual environment in which students can learn dentistry-specific motor patterns for surgery since they facilitate deliberate practice in a controlled environment. Whilst this system has the potential for changing the way in which practical dental teaching is delivered, a key step prior to full adoption in the curriculum is an analysis of the validity of this tool.

Early on this, we investigated the construct validity of the ‘Simodont’ during the induction of this system at the University of Leeds. Since no students had used this system before, there was a unique opportunity to investigate whether the system was able to discriminate between differing levels of surgical experience (i.e. difference across years of study) whilst controlling for experience on the simulator.

The results of this study showed that the Simodont is able to discriminate between novice and experienced students, with performance increasingly linearly as real-world dental experience increased. We also noted a speed-accuracy trade-off in performance, which resembled a U-shaped curve: Year 3 students took longer to complete the task relative to the other years.

These results align well with the literature on motor skill acquisition (Diedrichsen & Kornysheva, 2015). Our results show that at the beginning of dental education, students tend to take less time to perform the task but are less accurate. As they start to practise, they sacrifice time for accuracy, displaying a speed accuracy trade-off (hallmark of motor skill learning), which is reflective of the first phase of learning. This is followed by the ‘middle phase’ of learning where the time to perform the task decreases and accuracy increases, as more experience is gained. This work demonstrates how the use of simulation can provide insights into the processes underlying dental skill acquisition.

## 7.3 Early Motor and Academic Aptitude Assessment

Given the time and cost associated with dental training, the development of valid and reliable assessments of individuals who have the potential to successfully practice dentistry is imperative. In this thesis, we probed the issue of early assessment in three different ways.

First, we asked what traits were being measured in the multi-mini interviews used to select prospective undergraduate students at the University of Leeds. We found that surprisingly, despite 10 different assessment approaches, most of the variance in performance could be attributed to two underlying factors. The first related to six stations (presentation, memory, ethics, interpretation, and insight) and reflected the ability to communicate (with the ability to show empathy), analyse and interpret data, describe, show ethical awareness and reasoning and provide personal insight. Thus, factor 1 was labelled as “soft skill”. The second factor appeared to represent sensorimotor skills as four stations (Origami, ‘Simodont’, the Kinematic Assessment Tool (KAT) and the tangram assessment) loaded most highly on it. All four stations related to manual dexterity performance with the ability to follow complexed instructions, and thus, this second factor was labelled as “sensorimotor” skills.

Given that dental education requires more than soft and sensorimotor skills, dental educators should consider the design of their MMI stations so that they more readily map on to or assess different domains essential for potential dental students e.g. such as required for graduating dentist approved by the Association for Dental Education in Europe (ADEE) or the American Dental Education Association (ADEA).

Second, Chapter 5 investigated whether a particular measure of motor performance (the Kinematic Assessment tool) could be used to provide reliable measures of dental students' motor abilities. Interestingly, the findings showed no change in dental students' motor performance over time. However, there was a significant moderate positive correlation between the KAT scores at the interview process and in year 5, indicating strong test-retest reliability of the measure. Thus, there may be potential to use such a tool to assess motor skill abilities with respect to a student's suitability for a dental programme.

Finally, Chapter 6 investigated the predictive ability of the soft skills and visuomotor skills examined during the MMIs in predicting academic performance (both global performance and performance on specific soft skills and visuomotor tasks assessed over the course of the dental programme). These results demonstrated that the MMI assessments related to soft skills correlated with several modules and thus may be useful indicators of undergraduate performance. In contrast, the visuomotor skills had little correlation. Given this lack of relationship (and the clear relationship between motor skills and safe dental practice), we need to reconsider the approaches used to assess motor aptitude at the earliest stages of training (and perhaps beforehand). We propose that it is particularly important to ensure that the assessments are relevant and specific to the demands of dentistry. The positive transfer theory in psychology suggests that improvements in one motor task can lead to improvement in another related task (Lugassy et al., 2018), but the growing consensus in motor learning literature is that in order for performance transfer, the two performances should be as similar as possible (Braun, Mehring, & Wolpert, 2010; Wolpert et al., 2011) and thus, a challenge for the dental education field is to identify what core characteristics need to be assessed to develop the necessary tools for predicting subsequent dental performance.

## 7.4 The role of simulation in dental education

With an increasing global focus on patient safety, medical errors and changes in health care delivery, the role of simulation in dental education has gained substantial interest in recent years. We examined the state-of-art in dental education through an international workshop as reported in Appendix C. The result of the workshop was a consensus report that detailed the role of simulation in developing skilled dentists. It is clear from this work that there is great potential in VR simulation technology and that a great degree of potential is already being realised by educators from across the globe.

## 7.5 Summary

In closing, this thesis has examined topics of central importance to dental education- whether we can usefully predict academic and sensorimotor performance in dental students through early stage assessment. There was a particularly strong focus on the use of VR haptic simulation and objective measures of sensorimotor control – both relatively novel areas of investigation in this field and the findings from this thesis suggest there is potential for exploring their utility in further detail. The value of VR-based simulation is likely to be much broader than prediction alone and holds promise in transforming the way dental students are educated. It is with this perspective that this thesis culminated in contributing towards an international consensus on the current state of the art on simulation in dental education and it is with excitement that we look forwards to seeing the development of these areas over the coming years.

## 7.6 Limitations

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

1. In chapter 3, year 2 data were not available as a result of technical issue that resulted in the data not being stored or saved in the server. Thus, year 2 data was not included in the analysis which resulted in inability to capture their performances and compare with other year groups.

2. In the MMIs the interviewees were informed beforehand that the ‘Simodont’ and the KAT stations scores were not included in the MMI scores and therefore did not contribute to the total MMI score. As a result of that, this may have affected the incentives of the interviewees and thus their motivation may have been different especially to the students who their MMIs ended with the digital stations (‘Simodont’ and KAT).

3. In Chapter 5 there were difficulty in recruiting dental students, this could possibly due to their busy timetables as well as students being in placements which requires them to be outside the dental school and also preparing for their final fifth year examinations. The aim was to recruit at least more than half of the cohort but unfortunately, we were only able to recruit 30 students only. This problem lead to a compromise in the statistical power which could have affected the results of the study by showing no change in performance of the dental students at year 0 and year 5.

## 7.7 Recommendation/considerations for future work

Based on the findings from this thesis, the following consideration would be beneficial:

1. Restructuring the design of the MMI stations so that it maps or assesses different domains essential for potential dental students based on published papers. Documents that presented the competencies required for graduating dentist approved by the Association for Dental Education in Europe (ADEE) or the American Dental Education Association (ADEA) might be useful although it is mainly for the new general dentist (ADEA House of Delegates, 2011; Cowpe et al., 2010).

2. Using the MMI stations which were able to correlate mostly to the curriculum module and excluding the ones that did not or assessed a skill which was not related or considered essential for a potential dental student. Redesigning new stations that assess new domains (such as problem-solving skills) which were previously not assessed in the MMIs.

3. All MMI stations should be counted stations towards the MMI score as this will ensure that the students have attempted their best in each individual station.

4. When selecting the manual dexterity tool/test it is important to ensure that they are relevant and specific to the demands of dentistry. The positive transfer theory suggests that improvement in one motor task leads to improvement in another task (Lugassy et al., 2018), however, others believes that in order for the transfer to actually occur the two performances should be as similar as possible meaning that the transfer

relies on identical elements between two performances (Braun et al., 2010; Wolpert et al., 2011).

5. Investigating the manual dexterity tool/test in several aspects as a predictive tool, assessment tool as well as a motor monitoring tool. Although predictive ability will provide information regarding the dental students whom are more likely to excel in dentistry but its usefulness as an assessment tool and as a motor monitoring tool is very beneficial as this will help in providing a beforehand support to the dental students along their dental course. Thus, ensuring students are having a smoother learning journey and this will benefit the dental students as well as the tutors.

It is also recommended when investigating manual dexterity tool/test for motor improvement over time, this assessment need to take place at two different stages, after completion of preclinical training and clinical training. In order to have a complete understanding of their potential roles.

6. Exploration of the effect of deliberate practise on fine motor skills acquisition (K Anders Ericsson, 2004) . Deliberate practise is a training framework that has nine  features that it relies on to achieve medical educational goals, of which are focused and repetitive practise that leads to a rigorous assessment that yield feedback from simulators or teachers (McGaghie, Issenberg, Petrusa, & Scalese, 2010). The Simodont and other virtual reality simulator offer a unique research opportunity in this area.

# References


Ackerman, P L, & Cianciolo, A. T. (2000). Cognitive, perceptual-speed, and psychomotor determinants of individual differences during skill acquisition. *Journal of Experimental Psychology. Applied*, *6*(4), 259–290. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/11218338

Ackerman, Phillip L. (1988). Determinants of individual differences during skill acquisition: Cognitive abilities and information processing. *Journal of Experimental Psychology: General*, *117*(3), 288–318. https://doi.org/10.1037/0096-3445.117.3.288

Ada. (2017). *Dental Admission Test (DAT) 2017 Program Guide*. Retrieved from http://www.ada.org/~/media/ADA/Education and Careers/Files/dat_examinee_guide.ashx

ADEA House of Delegates. (2011). ADEA competencies for the new general dentist. *Journal of Dental Education*, *75*(7), 932–935.

Aggarwal, R., & Darzi, A. (2006). Technical-Skills Training in the 21st Century. *New England Journal of Medicine*, *355*(25), 2695–2696. https://doi.org/10.1056/NEJMe068179

Al-Mussawi, R. M., & Farid, F. (2016). Computer-Based Technologies in Dentistry: Types and Applications. *Journal of Dentistry (Tehran, Iran)*, *13*(3), 215–222. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/28392819

Al-Nasir, F. A., & Robertson, A. S. (2001). Can selection assessments predict students' achievements in the premedical year?: a study at Arabian Gulf University. *Education for Health (Abingdon, England)*, *14*(2), 277–286. https://doi.org/10.1080/13576280110056618

Al-Rukban, M. O., Munshi, F. M., Abdulghani, H. M., & Al-Hoqail, I. (2010). The ability of the pre-admission criteria to predict performance in a Saudi medical school. *Saudi Medical Journal*, *31*(5), 560–564. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/20464048

Al-Saud, L. M., Mushtaq, F., Mann, R. P., Mirghani, I., Balkhoyor, A., Harris, R., … Manogue, M. (2019). Early assessment with a virtual reality haptic simulator predicts performance in clinical practice. *BMJ Simulation and Technology Enhanced Learning*, bmjstel-2018-000420. https://doi.org/10.1136/bmjstel-2018-000420

Al-Saud, L. M. S., Mushtaq, F., Allsop, M. J., Culmer, P. C., Mirghani, I., Yates, E., … Manogue, M. (2016). Feedback and motor skill acquisition using a haptic dental simulator. *European Journal of Dental Education*, *11*(4), 1–8. https://doi.org/10.1111/eje.12214

Alaki, Shinawi, L. A., Yamani, I., Hassan, M. H. A., Tekian, A., & Park, Y. S. (2016). Gathering validity evidence in the use of multiple mini-interviews as an admission tool for dental students: Preliminary evidence from Saudi Arabia. *Medical Teacher*, *38 Suppl 1*(sup1), S45-51. https://doi.org/10.3109/0142159X.2016.1142510

Alaki, Yamany, I. A., Shinawi, L. A., Hassan, M. H. A., & Tekian, A. (2016). Can Multiple Mini-Interviews Predict Academic Performance of Dental Students? A Two-Year Follow-Up. *Journal of Dental Education*, *80*(11), 1376–1383. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/27803210

Albanese, M. A., Snow, M. H., Skochelak, S. E., Huggett, K. N., & Farrell, P. M. (2003). Assessing personal qualities in medical school admissions. *Academic Medicine : Journal of the Association of American Medical Colleges*, *78*(3), 313–321. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/12634215

Alcañiz, M., Grau, V., Monserrat, C., Juan, C., & Albalat, S. (1999). A system for the simulation and planning of orthodontic treatment using a low cost 3D laser scanner for dental anatomy capturing. *Studies in Health Technology and Informatics*, *62*, 8–14. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/10538404

Allareddy, V., Howell, T. H., & Karimbux, N. Y. (2012). Association between students' dental admission test scores and performance on comprehensive clinical exams. *Journal of Dental Education*, *76*(2), 168–173. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/22319081

Anderson, J., Hughes, D., & Wakeford, R. (1980). Medical student selection: a tentative attempt to establish a code of practice. *British Medical Journal*, *280*(6225), 1216–1218. https://doi.org/10.1136/bmj.280.6225.1216

Andréia, M., Rodrigues, F., Barbosa, R. G., Neto, M. E. B., & Ribeiro, I. M. M. P. (2004). *A Framework for Orthodontic Treatment Simulation*. Retrieved from https://pdfs.semanticscholar.org/1dd8/5422eae3bf649fa5e87555154dc317213d7d.pdf

Andriole, D. A., Jeffe, D. B., & Whelan, A. J. (2004). What predicts surgical internship performance? *American Journal of Surgery*, *188*(2), 161–164. https://doi.org/10.1016/j.amjsurg.2004.03.003

Arane, K., Behboudi, A., & Goldman, R. D. (2017). Virtual reality for pain and anxiety management in children. *Canadian Family Physician Medecin de Famille Canadien*, *63*(12), 932–934. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/29237632

Barbour, M. E., & Sandy, J. R. (2014). Multiple mini interviews for selection of dental students: influence of gender and starting station. *Journal of Dental Education*, *78*(4), 589–596. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/24706689

Basco, W. T., Gilbert, G. E., Chessman, A. W., & Blue, A. V. (2000). The ability of a medical school admission process to predict clinical performance and patients' satisfaction. *Academic Medicine : Journal of the Association of American Medical Colleges*, *75*(7), 743–747. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/10926028

Basdogan, C., & Srinivasan, M. A. (2002). Haptic Rendering in Virtual Environments. Retrieved from http://www.sensable.com/community/index.htm

Beier, U. S., Kapferer, I., Ostermann, H., Staudinger, R., & Dumfahrt, H. (2010). Impact of a novel dental school admission test on student performance at Innsbruck Medical University, Austria. *Journal of Dental Education*, *74*(5), 531–538. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/20442431

Ben-Gal, G, Weiss, E., Gafni, N., & Ziv, A. (2011). Preliminary assessment of faculty and student perception of a haptic virtual reality simulator for training dental manual dexterity. *Journal of Dental Education*, *75*(4), 496–504.

Ben-Gal, G, Weiss, E. I., Gafni, N., & Ziv, A. (2013). Testing manual dexterity using a virtual reality simulator: reliability and validity. *European Journal of Dental Education : Official Journal of the Association for Dental Education in Europe*, *17*(3), 138–142. https://doi.org/10.1111/eje.12023

Ben-Gal, Gilad, Katorza, L., Weiss, E. I., & Ziv, A. (2017). Testing Motor Learning Curves Among Dental Students. *Journal of Dental Education*, *81*(10), 1171–1178. https://doi.org/10.21815/JDE.017.076

Benbassat, J., & Baumal, R. (2007). Uncertainties in the selection of applicants for medical school. *Advances in Health Sciences Education*, *12*(4), 509–521. https://doi.org/10.1007/s10459-007-9076-0

Bergman, A. V, Susarla, S. M., Howell, T. H., & Karimbux, N. Y. (2006). Dental Admission Test scores and performance on NBDE Part I, revisited. *Journal of Dental Education*, *70*(3), 258–262. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/16522754

Bhatti, M. A., & Anwar, M. (2012). Does entry test make any difference on the future performance of medical students? *JPMA. The Journal of the Pakistan Medical Association*, *62*(7), 664–668. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/23866511

Boyle, A. M., & Santelli, J. C. (1986). Assessing psychomotor skills: the role of the Crawford Small Parts Dexterity Test as a screening instrument. *Journal of Dental Education*, *50*(3), 176–179. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/3456367

Bracken, N. R. (2006). *Psychoeducational Assessment of Preschool Children*.

Brannick, M. T., Grichanik, M., Nazian, S. J., Wahi, M., & Goldin, S. B. (2013). Emotional Intelligence and Medical School Performance: A Prospective Multivariate Study. *Medical*

*Science Educator*, *23*(4), 628–636. https://doi.org/10.1007/BF03341690

Braun, D. A., Mehring, C., & Wolpert, D. M. (2010). Structure learning in action. *Behavioural Brain Research*, *206*(2), 157–165. https://doi.org/10.1016/j.bbr.2009.08.031

Brothers, T. E., & Wetherholt, S. (2007). Importance of the Faculty Interview During the Resident Application Process. *Journal of Surgical Education*, *64*(6), 378–385. https://doi.org/10.1016/j.jsurg.2007.05.003

Brownell, K., Lockyer, J., Collin, T., & Lemay, J.-F. (2007). Introduction of the multiple mini interview into the admissions process at the University of Calgary: acceptability and feasibility. *Medical Teacher*, *29*(4), 394–396. https://doi.org/10.1080/01421590701311713

Brydges, R., Carnahan, H., Backstein, D., & Dubrowski, A. (2007). Application of Motor Learning Principles to Complex Surgical Tasks: Searching for the Optimal Practice Schedule. *Journal of Motor Behavior*, *39*(1), 40–48. https://doi.org/10.3200/JMBR.39.1.40-48

Buchanan. (2001). Use of simulation technology in dental education. *Journal of Dental Education*, *65*(11), 1225–1231.

Buchanan, J. A. (2004). Experience with virtual reality-based technology in teaching restorative dental procedures. *Journal of Dental Education*, *68*(12), 1258–1265.

Cabrera, M. A. M., & Nguyen, N. T. (2001). Situational Judgment Tests: A Review of Practice and Constructs Assessed. *International Journal of Selection and Assessment*, *9*(1&2), 103–113. https://doi.org/10.1111/1468-2389.00167

Callahan, C. A., Hojat, M., Veloski, J., Erdmann, J. B., & Gonnella, J. S. (2010). The predictive validity of three versions of the MCAT in relation to performance in medical school, residency, and licensing examinations: a longitudinal study of 36 classes of Jefferson Medical College. *Academic Medicine : Journal of the Association of American Medical Colleges*, *85*(6), 980–987. https://doi.org/10.1097/ACM.0b013e3181cece3d

Campagna-Vaillancourt, M., Manoukian, J., Razack, S., & Nguyen, L. H. P. (2014). Acceptability and reliability of multiple mini interviews for admission to otolaryngology residency. *Laryngoscope*. https://doi.org/10.1002/lary.24122

Carr, S. E. (2009). Emotional intelligence in medical students: does it correlate with selection measures? *Medical Education*, *43*(11), 1069–1077. https://doi.org/10.1111/j.1365-2923.2009.03496.x

Carroll, A. M., & Schuster, G. M. (2015). Correlation Between Students' Dental Admission Test Scores and Performance on a Dental School's Competency Exam. *Journal of Dental Education*, *79*(11), 1325–1329. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/26522638

Carrothers, R. M., Gregory, S. W., & Gallagher, T. J. (2000). Measuring emotional intelligence of medical school applicants. *Academic Medicine : Journal of the Association of American Medical Colleges*, *75*(5), 456–463. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/10824770

Chen, M. K., Podshadley, D. W., & Shrock, J. G. (1967). A factorial study of some psychological, vocational interest, and mental ability variables as predictors of success in dental school. *Journal of Applied Psychology*, *51*(3), 236–241. https://doi.org/10.1037/h0024680

Chen, X., Sun, P., & Liao, D. (2018). A patient-specific haptic drilling simulator based on virtual reality for dental implant surgery. *International Journal of Computer Assisted Radiology and Surgery*, *13*(11), 1861–1870. https://doi.org/10.1007/s11548-018-1845-0

Christian, M. S., Edwars, B. D., & Bradeley, J. C. (2010). Situational judgment tests: Constructs assessed and a meta-analysis of their criterion-related validities. *Personnel Psychology*, *63*(1), 83–117. https://doi.org/10.1111/j.1744-6570.2009.01163.x

Churchland, M. M., Cunningham, J. P., Kaufman, M. T., Foster, J. D., Nuyujukian, P., Ryu, S. I., & Shenoy, K. V. (2012). Neural population dynamics during reaching. *Nature*, *487*(7405), 51–56. https://doi.org/10.1038/nature11129

Cisek, P. (2012). Making decisions through a distributed consensus. *Current Opinion in Neurobiology*, *22*, 927–936. https://doi.org/10.1016/j.conb.2012.05.007

Cleland, J. A., Dowell, J., McLachlan, J., Nicholson, S., & Patterson, F. (2012). Identifying best practice in the selection of medical students (literature review and interview survey). *General Medical Council*, (November 2012), 1–106. Retrieved from http://www.gmc-uk.org/Identifying_best_practice_in_the_selection_of_medical_students.pdf_51119804.pdf

Cohen-Schotanus, J., Muijtjens, A. M. M., Reinders, J. J., Agsteribbe, J., van Rossum, H. J. M., & van der Vleuten, C. P. M. (2006). The predictive validity of grade point average scores in a partial lottery medical school admission system. *Medical Education*, *40*(10), 1012–1019. https://doi.org/10.1111/j.1365-2929.2006.02561.x

Corrêa, C. G., Machado, M. A. de A. M., Ranzini, E., Tori, R., & Nunes, F. de L. S. (2017). Virtual Reality simulator for dental anesthesia training in the inferior alveolar nerve block. *Journal of Applied Oral Science : Revista FOB*, *25*(4), 357–366. https://doi.org/10.1590/1678-7757-2016-0386

Costa, R. M. (2011). A selectionist account of de novo action learning. *Current Opinion in Neurobiology*, *21*(4), 579–586. https://doi.org/10.1016/j.conb.2011.05.004

Costa, R. M., Cohen, D., & Nicolelis, M. A. L. (2004). Differential Corticostriatal Plasticity during Fast and Slow Motor Skill Learning in Mice. *Current Biology*, *14*(13), 1124–1134. https://doi.org/10.1016/j.cub.2004.06.053

Cowpe, J., Plasschaert, A., Harzer, W., Vinkka-Puhakka, H., & Walmsley, A. D. (2010). Profile and competences for the graduating European dentist - update 2009. *European Journal of Dental Education*, *14*(4), 193–202. https://doi.org/10.1111/j.1600-0579.2009.00609.x

Cox , King , Hutchinson , McAvoy, E. (2006). *Understanding Doctors' Performance.* Oxford: Radcliffe Publishing;

Cox, M., Quinn, B., Shahriari-Rad, A., Vervoorn, M., Wesselink, P., & de Boer, I. (2015). A Collaborative Review of the Field of Simulation-Enhanced Dental Education. https://doi.org/10.13140/RG.2.1.2347.7202

Coy, K., McDougall, H., & Sneed, M. (2003). Issues regarding practical validity and gender bias of the Perceptual Abilities Test (PAT). *Journal of Dental Education*, *67*(1), 31–37. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/12540103

Cullen, M. J., Sackett, P. R., & Lievens, F. (2006). Threats to the Operational Use of Situational Judgment Tests in the College Admission Process. *International Journal of Selection and Assessment*, *14*(2), 142–155. https://doi.org/10.1111/j.1468-2389.2006.00340.x

Culmer, P. R., Levesley, M. C., Mon-Williams, M., & Williams, J. H. G. (2009). A new tool for assessing human movement: The Kinematic Assessment Tool. *Journal of Neuroscience Methods*, *184*(1), 184–192. https://doi.org/10.1016/j.jneumeth.2009.07.025

Curtis, D. A., Lind, S. L., Brear, S., & Finzen, F. C. (2007). The correlation of student performance in preclinical and clinical prosthodontic assessments. *Journal of Dental Education*, *71*(3), 365–372. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/17389571

Cutler, N., Balicki, M., Finkelstein, M., Wang, J., Gehlbach, P., McGready, J., … Handa, J. T. (2013). Auditory force feedback substitution improves surgical precision during simulated ophthalmic surgery. *Investigative Ophthalmology & Visual Science*, *54*(2), 1316–1324. https://doi.org/10.1167/iovs.12-11136

Dalaya, M., Ishaquddin, S., Ghadage, M., & Hatte, G. (2015). An interesting review on soft skills and dental practice. *Journal of Clinical and Diagnostic Research : JCDR*, *9*(3), ZE19-21. https://doi.org/10.7860/JCDR/2015/12725.5719

Dayan, E., & Cohen, L. G. (2011). Neuroplasticity Subserving Motor Skill Learning. *Neuron*, *72*(3), 443–454. https://doi.org/10.1016/j.neuron.2011.10.008

de Andrés, A. G., Sánchez, E., Hidalgo, J. J., & Díaz, M. J. (2004). Appraisal of psychomotor skills of dental students at University Complutense of Madrid. *European Journal of Dental Education : Official Journal of the Association for Dental Education in Europe*, *8*(1), 24–30. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/14717687

de Virgilio, C. (2010). Predicting Performance on the American Board of Surgery Qualifying and Certifying Examinations. *Archives of Surgery*, *145*(9), 852. https://doi.org/10.1001/archsurg.2010.177

DeZee, K. J., Magee, C. D., Rickards, G., Artino, A. R., Gilliland, W. R., Dong, T., … Durning, S. J. (2014). What aspects of letters of recommendation predict performance in medical school? Findings from one institution. *Academic Medicine : Journal of the Association of American Medical Colleges*, *89*(10), 1408–1415. https://doi.org/10.1097/ACM.0000000000000425

Diedrichsen, J., & Kornysheva, K. (2015). Motor skill learning between selection and execution. *Trends in Cognitive Sciences*, *19*(4), 227–233. https://doi.org/10.1016/j.tics.2015.02.003

Diedrichsen, J., Verstynen, T., Lehman, S. L., & Ivry, R. B. (2005). Cerebellar involvement in anticipating the consequences of self-produced actions during bimanual movements. *Journal of Neurophysiology*, *93*(2), 801–812. https://doi.org/10.1152/jn.00662.2004

Diedrichsen, J., Wiestler, T., & Krakauer, J. W. (2013). Two Distinct Ipsilateral Cortical Representations for Individuated Finger Movements. *Cerebral Cortex*, *23*(6), 1362–1377. https://doi.org/10.1093/cercor/bhs120

Donnon, T., Paolucci, E. O., & Violato, C. (2007). The Predictive Validity of the MCAT for Medical School Performance and Medical Board Licensing Examinations: A Meta-Analysis of the Published Research. *Academic Medicine*, *82*(1), 100–106. https://doi.org/10.1097/01.ACM.0000249878.25186.b7

Dore, K. L., Kreuger, S., Ladhani, M., Rolfson, D., Kurtz, D., Kulasegaram, K., … Reiter, H. I. (2010). The Reliability and Acceptability of the Multiple Mini-Interview as a Selection Instrument for Postgraduate Admissions. *Academic Medicine*, *85*, S60–S63. https://doi.org/10.1097/ACM.0b013e3181ed442b

Dougherty, P. J., Walter, N., Schilling, P., Najibi, S., & Herkowitz, H. (2010). Do Scores of the USMLE Step 1 and OITE Correlate with the ABOS Part I Certifying Examination?: A Multicenter Study. *Clinical Orthopaedics and Related Research®*, *468*(10), 2797–2802. https://doi.org/10.1007/s11999-010-1327-3

Dowell, J., Lynch, B., Till, H., Kumwenda, B., & Husbands, A. (2012). The multiple mini-interview in the UK context: 3 years of experience at Dundee. *Medical Teacher*, *34*(4), 297–304. https://doi.org/10.3109/0142159X.2012.652706

Dubrowski, A., Backstein, D., Abughaduma, R., Leidl, D., & Carnahan, H. (2005). The influence of practice schedules in the learning of a complex bone-plating surgical task. *The American Journal of Surgery*, *190*(3), 359–363. https://doi.org/10.1016/j.amjsurg.2005.03.027

Dunleavy, D. M., Kroopnick, M. H., Dowd, K. W., Searcy, C. A., & Zhao, X. (2013). The Predictive Validity of the MCAT Exam in Relation to Academic Performance Through Medical School. *Academic Medicine*, *88*(5), 666–671. https://doi.org/10.1097/ACM.0b013e3182864299

Duong, J. K. T., Gardner, K., & Rucker, L. M. (2010). Development and retention of fine psychomotor skills: implications for the aging dentist. *Journal (Canadian Dental Association)*, *76*, a25. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/20633335

Dutã, Amariei, Bogdan, C., Popovici, D., Ionescu, N., & Nuca, C. I. (2011). An Overview of Virtual and Augmented Reality in Dental Education. *Oral Health and Dental Management*, *10*(1), 42–49.

Eaton, K., Reynolds, P., Grayden, S., & Wilson, N. (2008). A vision of dental education in the third millennium. *British Dental Journal*, *205*(5), 261–271. https://doi.org/10.1038/sj.bdj.2008.736

Edwards, D., Friedman, T., & Pearce, J. (2013). Same admissions tools, different outcomes: a critical perspective on predictive validity in three undergraduate medical schools. *BMC Medical Education*, *13*(1), 173. https://doi.org/10.1186/1472-6920-13-173

Edwards, J. C., Elam, C. L., & Wagoner, N. E. (2001). An admission model for medical schools. *Academic Medicine : Journal of the Association of American Medical Colleges*, *76*(12), 1207–1212. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/11739042

Elam, C. L., Stratton, T. D., Scott, K. L., Wilson, J. F., & Lieber, A. (2002). Review, deliberation, and voting: a study of selection decisions in a medical school admission committee. *Teaching and Learning in Medicine*, *14*(2), 98–103. https://doi.org/10.1207/S15328015TLM1402_06

Emery, J. L., Bell, J. F., & Vidal Rodeiro, C. L. (2011). The BioMedical Admissions Test for medical student selection: issues of fairness and bias. *Medical Teacher*, *33*(1), 62–71. https://doi.org/10.3109/0142159X.2010.528811

Ericsson, K. A., & Lehmann, A. C. (1996). EXPERT AND EXCEPTIONAL PERFORMANCE: Evidence of Maximal Adaptation to Task Constraints. *Annual Review of Psychology*, *47*(1), 273–305. https://doi.org/10.1146/annurev.psych.47.1.273

Ericsson, K Anders. (2004). Deliberate practice and the acquisition and maintenance of expert performance in medicine and related domains. *Academic Medicine : Journal of the Association of American Medical Colleges*, *79*(10 Suppl), S70-81. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/15383395

Ericsson, K Anders, Krampe, R. T., & Tesch-Romer, C. (1993). *The Role of Deliberate Practice in the Acquisition of Expert Performance*. *Psychological Review* (Vol. 100). Retrieved from http://projects.ict.usc.edu/itw/gel/EricssonDeliberatePracticePR93.pdf

Escobar-Castillejos, D., Noguez, J., Neri, L., Magana, A., & Benes, B. (2016). A Review of Simulators with Haptic Devices for Medical Training. *Journal of Medical Systems*, *40*(4), 104. https://doi.org/10.1007/s10916-016-0459-8

Eva, K. W., & Macala, C. (2014). Multiple mini-interview test characteristics: ’tis better to ask candidates to recall than to imagine. *Medical Education*, *48*(6), 604–613. https://doi.org/10.1111/medu.12402

Eva, K. W., Reiter, H. I., Rosenfeld, J., Trinh, K., Wood, T. J., & Norman, G. R. (2012). Association between a medical school admission process using the multiple mini-interview and national licensing examination scores. *JAMA*, *308*(21), 2233–2240. https://doi.org/10.1001/jama.2012.36914

Eva, K. W., Rosenfeld, J., Reiter, H. I., & Norman, G. R. (2004). An admissions OSCE: the multiple mini-interview. *Medical Education*, *38*(3), 314–326. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/14996341

Evans, J. G., & Dirks, S. J. (2001). Relationships of admissions data and measurements of psychological constructs with psychomotor performance of dental technology students. *Journal of Dental Education*, *65*(9), 874–882. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/11569603

Fager, P. J., & von Wowern, P. (2004). The use of haptics in medical applications. *The International Journal of Medical Robotics + Computer Assisted Surgery : MRCAS*, *1*, 36–42. https://doi.org/10.1002/rcs.4

Ferguson, E., James, D., O’Hehir, F., Sanders, A., & McManus, I. C. (2003). Pilot study of the roles of personality, references, and personal statements in relation to performance over the five years of a medical degree * Commentary: How to derive causes from correlations in educational studies. *BMJ*, *326*(7386), 429–432. https://doi.org/10.1136/bmj.326.7386.429

Ferguson, Eamonn, Sanders, A., O’Hehir, F., & James, D. (2000). Predictive validity of personal statements and the role of the five-factor model of personality in relation to medical training. *Journal of Occupational and Organizational Psychology*, *73*(3), 321–344. https://doi.org/10.1348/096317900167056

Ferguson, Eamonn, Semper, H., Yates, J., Fitzgerald, J. E., Skatova, A., & James, D. (2014).

The “dark side” and “bright side” of personality: when too much conscientiousness and too little anxiety are detrimental with respect to the acquisition of medical knowledge and skill. *PloS One*, *9*(2), e88606. https://doi.org/10.1371/journal.pone.0088606

Flatters, I., Hill, L. J. B., Williams, J. H. G., Barber, S. E., & Mon-Williams, M. (2014). Manual Control Age and Sex Differences in 4 to 11 Year Old Children. *PLoS ONE*, *9*(2), e88692. https://doi.org/10.1371/journal.pone.0088692

Flatters, I., Mushtaq, F., Hill, L. J. B., Rossiter, A., Jarrett-Peet, K., Culmer, P., … Mon-Williams, M. (2014). Children’s head movements and postural stability as a function of task. *Experimental Brain Research*, *232*(6), 1953–1970. https://doi.org/10.1007/s00221-014-3886-0

Foley, J. I., & Hijazi, K. (2013). The admissions process in a graduate-entry dental school: can we predict academic performance? *British Dental Journal*, *214*(2), E4. https://doi.org/10.1038/sj.bdj.2013.56

Freeberg, N. E. (1966). Construct validity of a paper-and-pencil test of manual dexterity. *Perceptual and Motor Skills*, *22*(1), 200. https://doi.org/10.2466/pms.1966.22.1.200

Fried, M. P., Satava, R., Weghorst, S., Gallagher, A., Sasaki, C., Ross, D., … Arora, H. (2005). *The Use of Surgical Simulators to Reduce Errors*. *Advances in Patient Safety: From Research to Implementation (Volume 4:Programs, Tools, and Products)*. Agency for Healthcare Research and Quality (US). Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/21250030

Fruen, M. A. (1980). Medical school admissions interview: pro and con. *Journal of Medical Education*, *55*(7), 630–631. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/7411569

Fugill. (2013). Defining the purpose of phantom head. *European Journal of Dental Education*, *17*(1), e1–e4. https://doi.org/10.1111/eje.12008

Furman, E., Jasinevicius, T. R., Bissada, N. F., Victoroff, K. Z., Skillicorn, R., & Buchner, M. (2009). Virtual reality distraction for pain control during periodontal scaling and root planing procedures. *Journal of the American Dental Association (1939)*, *140*(12), 1508–1516. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/19955069

Gaba, D. M. (2004). The future vision of simulation in health care. *Quality and Safety in Health Care*, *13*(suppl_1), i2–i10. https://doi.org/10.1136/qshc.2004.009878

Gafni, N., Moshinsky, A., Eisenberg, O., Zeigler, D., & Ziv, A. (2012). Reliability estimates: behavioural stations and questionnaires in medical school admissions. *Medical Education*, *46*(3), 277–288. https://doi.org/10.1111/j.1365-2923.2011.04155.x

Gale, T. C. E., Roberts, M. J., Sice, P. J., Langton, J. A., Patterson, F. C., Carr, A. S., … Davies, P. R. F. (2010). Predictive validity of a selection centre testing non-technical skills for recruitment to training in anaesthesia. *British Journal of Anaesthesia*, *105*(5), 603–609. https://doi.org/10.1093/bja/aeq228

Gallagher,  a. G., Ritter, E. M., & Satava, R. M. (2003). Fundamental principles of validation, and reliability: Rigorous science for the assessment of surgical education and training. *Surgical Endoscopy and Other Interventional Techniques*, *17*, 1525–1529. https://doi.org/10.1007/s00464-003-0035-4

Gallagher, A. G., McClure, N., McGuigan, J., Crothers, I., & Browning, J. (1999). Virtual Reality Training in Laparoscopic Surgery: A Preliminary Assessment of Minimally Invasive Surgical Trainer Virtual Reality (MIST VR). *Endoscopy*, *31*(4), 310–313. https://doi.org/10.1055/s-1999-15

Gallivan, J. P., McLean, D. A., Flanagan, J. R., & Culham, J. C. (2013). Where One Hand Meets the Other: Limb-Specific and Action-Dependent Movement Plans Decoded from Preparatory Signals in Single Human Frontoparietal Brain Areas. *Journal of Neuroscience*, *33*(5), 1991–2008. https://doi.org/10.1523/JNEUROSCI.0541-12.2013

Ganguly, K., & Carmena, J. M. (2009). Emergence of a Stable Cortical Map for Neuroprosthetic Control. *PLoS Biology*, *7*(7), e1000153. https://doi.org/10.1371/journal.pbio.1000153

Gansky, S. A., Pritchard, H., Kahl, E., Mendoza, D., Bird, W., Miller, A. J., & Graham, D. (2004). Reliability and validity of a manual dexterity test to predict preclinical grades. *Journal of Dental Education*, *68*(9), 985–994. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/15342660

General Dental Council. (2012). Preparing for practice, 1–104.

Gentaz, E., Baud-Bovy, G., & Luyat, M. (2008). The haptic perception of spatial orientations. *Experimental Brain Research*, *187*(3), 331–348. https://doi.org/10.1007/s00221-008-1382-0

Gibson, J. J. (1962). Observations on active touch. *Psychological Review*, *69*, 477–491. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/13947730

Giuliani, M., Lajolo, C., Clemente, L., Querqui, A., Viotti, R., Boari, A., & Miani, C. M. (2007). Is manual dexterity essential in the selection of dental students? *British Dental Journal*, *203*(3), 149–155. https://doi.org/10.1038/bdj.2007.688

Goldberg, A. E., Neifeld, J. P., Wolfe, L. G., & Goldberg, S. R. (2008). Correlation of manual dexterity with USMLE scores and medical student class rank. *The Journal of Surgical Research*, *147*(2), 212–215. https://doi.org/10.1016/j.jss.2008.02.050

Gorman, P. J., Meier, A. H., & Krummel, T. M. (1999). Simulation and virtual reality in surgical education: real or unreal? *Archives of Surgery (Chicago, Ill. : 1960)*, *134*(11), 1203–1208. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/10555634

Gottlieb, R., Vervoorn, J. M., & Buchanan, J. (2013). Simulation in Dentistry and Oral Health. In A. I. Levine, S. DeMaria, A. D. Schwartz, & A. J. Sim (Eds.), *The Comprehensive Textbook of Healthcare Simulation* (pp. 329–340). New York, NY: Springer New York. https://doi.org/10.1007/978-1-4614-5993-4

Gray, S. A., Deem, L. P., Sisson, J. A., & Hammrich, P. L. (2003). The predictive utility of computer-simulated exercises for preclinical technique performance. *Journal of Dental Education*, *67*(11), 1229–1233. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/14650504

Gray, S. A., Deem, L. P., & Straja, S. R. (2002). Are traditional cognitive tests useful in predicting clinical success? *Journal of Dental Education*, *66*(11), 1241–1245. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/12484675

Griffin, B., Yeomans, N. D., & Wilson, I. G. (2013). Students coached for an admission test perform less well throughout a medical course. *Internal Medicine Journal*, *43*(8), 927–932. https://doi.org/10.1111/imj.12171

Hahnloser, R. H. R., Kozhevnikov, A. A., & Fee, M. S. (2002). An ultra-sparse code underliesthe generation of neural sequences in a songbird. *Nature*, *419*(6902), 65–70. https://doi.org/10.1038/nature00974

Haibach, P., Reid, G., & Collier, D. (2011). *Motor Learning and Development*. Human Kinetics.

Haight, S. J., Chibnall, J. T., Schindler, D. L., & Slavin, S. J. (2012). Associations of medical student personality and health/wellness characteristics with their medical school performance across the curriculum. *Academic Medicine : Journal of the Association of American Medical Colleges*, *87*(4), 476–485. https://doi.org/10.1097/ACM.0b013e318248e9d0

Halpenny, D., Cadoo, K., Halpenny, M., Burke, J., & Torreggiani, W. C. (2010). The Health Professions Admission Test (HPAT) score and leaving certificate results can independently predict academic performance in medical school: do we need both tests? *Irish Medical Journal*, *103*(10), 300–302. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/21560500

Hänsel, M., Klupp, S., Graupner, A., Dieter, P., & Koch, T. (2010). Dresden Faculty selection procedure for medical students: what impact does it have, what is the outcome? *GMS Zeitschrift Fur Medizinische Ausbildung*, *27*(2), Doc25. https://doi.org/10.3205/zma000662

Heintze, U., Radeborg, K., Bengtsson, H., & Stenlåås, A. (2004). Assessment and evaluation of individual prerequisites for dental education. *European Journal of Dental Education*, *8*(4), 152–160. https://doi.org/10.1111/j.1600-0579.2004.00345.x

Helmreich, R. L. (1997). Managing human error in aviation. *Scientific American*, *276*(5), 62–67. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/11536800

Hikosaka, O., Nakamura, K., Sakai, K., & Nakahara, H. (2002). Central mechanisms of motor skill learning. *Current Opinion in Neurobiology*, *12*(2), 217–222. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/12015240

Hofmeister, M., Lockyer, J., & Crutcher, R. (2008). The acceptability of the multiple mini interview for resident selection. *Family Medicine*, *40*(10), 734–740. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/18979262

Hofmeister, M., Lockyer, J., & Crutcher, R. (2009). The multiple mini-interview for selection of international medical graduates into family medicine residency education. *Medical Education*, *43*(6), 573–579. https://doi.org/10.1111/j.1365-2923.2009.03380.x

Hojat, M., Erdmann, J. B., & Gonnella, J. S. (2013). Personality assessments and outcomes in medical education and the practice of medicine: AMEE Guide No. 79. *Medical Teacher*, *35*(7), e1267–e1301. https://doi.org/10.3109/0142159X.2013.785654

Hopson, L. R., Burkhardt, J. C., Stansfield, R. B., Vohra, T., Turner-Lawrence, D., & Losman, E. D. (2014). The Multiple Mini-Interview for Emergency Medicine Resident Selection. *The Journal of Emergency Medicine*, *46*(4), 537–543. https://doi.org/10.1016/j.jemermed.2013.08.119

Husbands, A., & Dowell, J. (2013). Predictive validity of the Dundee multiple mini-interview. *Medical Education*, *47*(7), 717–725. https://doi.org/10.1111/medu.12193

Husbands, A., Mathieson, A., Dowell, J., Cleland, J., & MacKenzie, R. (2014). Predictive validity of the UK clinical aptitude test in the final years of medical school: a prospective cohort study. *BMC Medical Education*, *14*(1), 88. https://doi.org/10.1186/1472-6920-14-88

Issenberg, Mcgaghie, W. C., Petrusa, E. R., Lee Gordon, D., & Scalese, R. J. (2005). Features and uses of high-fidelity medical simulations that lead to effective learning: a BEME systematic review*. *Medical Teacher*, *27*(1), 10–28. https://doi.org/10.1080/01421590500046924

Jasinevicius, T. R., Landers, M., Nelson, S., & Urbankova, A. (2004). An evaluation of two dental simulation systems: virtual reality versus contemporary non-computer-assisted. *Journal of Dental Education*, *68*(11), 1151–1162. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/15520234

Jenkins, I. H., Brooks, D. J., Nixon, P. D., Frackowiak, R. S., & Passingham, R. E. (1994). Motor sequence learning: a study with positron emission tomography. *The Journal of Neuroscience : The Official Journal of the Society for Neuroscience*, *14*(6), 3775–3790. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/8207487

Kami, A., Meyer, G., Jezzard, P., Adams, M. M., Turner, R., & Ungerleider, L. G. (1995). Functional MRI evidence for adult motor cortex plasticity during motor skill learning. *Nature*, *377*(6545), 155–158. https://doi.org/10.1038/377155a0

Kanfer, R., & Ackerman, P. L. (1989). Motivation and cognitive abilities: An integrative/aptitude-treatment interaction approach to skill acquisition. *Journal of Applied Psychology*, *74*(4), 657–690. https://doi.org/10.1037/0021-9010.74.4.657

Kao, E. C., Ngan, P. W., Wilson, S., & Kunovich, R. (1990). Wire-bending test as a predictor of preclinical performance by dental students. *Perceptual and Motor Skills*, *71*(2), 667–673. https://doi.org/10.2466/pms.1990.71.2.667

Kapoor, S., Arora, P., Kapoor, V., Jayachandran, M., & Tiwari, M. (2014). Haptics - Touchfeedback technology widening the horizon of medicine. *Journal of Clinical and Diagnostic Research*, *8*(3), 294–299.

Karni, A., Meyer, G., Rey-Hipolito, C., Jezzard, P., Adams, M. M., Turner, R., & Ungerleider, L. G. (1998). The acquisition of skilled motor performance: fast and slow experience-driven changes in primary motor cortex. *Proceedings of the National Academy of Sciences of the United States of America*, *95*(3), 861–868. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/9448252

Kay, E., Bennett, J., Allison, P., & Coombes, L. R. (2010). Evidence-informed dental student recruitment techniques. *BDJ*, *208*. https://doi.org/10.1038/sj.bdj.2010.105

Kelly, M., Dowell, J., Husbands, A., Kropmans, T., Jackson, A. E., Dunne, F., … Murphy, A. W. (2014). Can Multiple Mini Interviews work in an Irish setting? A feasibility study. *Irish Medical Journal*, *107*(7), 210–212. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/25226716

Kelly, M. E., Patterson, F., O'Flynn, S., Mulligan, J., & Murphy, A. W. (2018). A systematic review of stakeholder views of selection methods for medical schools admission. *BMC Medical Education*, *18*(1), 139. https://doi.org/10.1186/s12909-018-1235-x

Khera, G. (ASIT). (2011). *Simulation in Surgical Training*.

Killip, D. E., Fuller, J. L., & Kerber, P. E. (1979). The admission interview: the validity question. *Journal of Dental Education*, *43*(10 Pt 1), 547–551. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/289678

Kinoshita, H., Nagahata, M., Takano, N., Takemoto, S., Matsunaga, S., Abe, S., … Kawada, E. (2016). Development of a Drilling Simulator for Dental Implant Surgery. *Journal of Dental Education*, *80*(1), 83–90. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/26729688

Kirby, T. J. (1979). Dexterity testing and residents' surgical performance. *Transactions of the American Ophthalmological Society*, *77*, 294–307. Retrieved from http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=1311706&tool=pmcentrez&rendertype=abstract

Kneebone, R. L. (2009). Practice, Rehearsal, and Performance. *JAMA*, *302*(12), 1336. https://doi.org/10.1001/jama.2009.1392

Knorr, M., & Hissbach, J. (2014). Multiple mini-interviews: same concept, different approaches. *Medical Education*, *48*(12), 1157–1175. https://doi.org/10.1111/medu.12535

Komiyama, T., Sato, T. R., O'Connor, D. H., Zhang, Y.-X., Huber, D., Hooks, B. M., … Svoboda, K. (2010). Learning-related fine-scale specificity imaged in motor cortex circuits of behaving mice. *Nature*, *464*(7292), 1182–1186. https://doi.org/10.1038/nature08897

Kothe, C., Hissbach, J., & Hampe, W. (2013). The Hamburg selection procedure for dental students - introduction of the HAM-Nat as subject-specific test for study aptitude. *GMS Zeitschrift Für Medizinische Ausbildung*, *30*(4), Doc46. Retrieved from http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=3839074&tool=pmcentrez&rendertype=abstract

Kothe, C., Hissbach, J., & Hampe, W. (2014). Prediction of practical performance in preclinical laboratory courses - the return of wire bending for admission of dental students in Hamburg. *GMS Zeitschrift Für Medizinische Ausbildung*, *31*(2), Doc22. https://doi.org/10.3205/zma000914

Kramer, G. A. (1986). Predictive validity of the Dental Admission Test. *Journal of Dental Education*, *50*(9), 526–531. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/3462219

Kreiter, C. D., & Axelson, R. D. (2013). A Perspective on Medical School Admission Research and Practice Over the Last 25 Years. *Teaching and Learning in Medicine*, *25*(sup1), S50–S56. https://doi.org/10.1080/10401334.2013.842910

Kreiter, C. D., Yin, P., Solow, C., & Brennan, R. L. (2004). Investigating the Reliability of the Medical School Admissions Interview. *Advances in Health Sciences Education*, *9*(2), 147–159. https://doi.org/10.1023/B:AHSE.0000027464.22411.0f

Kröger, E., Dekiff, M., & Dirksen, D. (2017). 3D printed simulation models based on real patient situations for hands-on practice. *European Journal of Dental Education*, *21*(4), e119–e125. https://doi.org/10.1111/eje.12229

Kron, I. L., Kaiser, D. L., Nolan, S. P., Rudolf, L. E., Muller, W. H., & Jones, R. S. (1985). Can success in the surgical residency be predicted from preresidency evaluation? *Annals of Surgery*, *202*(6), 694–695. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/4073981

Laforce, R., & Doyon, J. (2001). Distinct contribution of the striatum and cerebellum to motor learning. *Brain and Cognition*, *45*(2), 189–211. https://doi.org/10.1006/brcg.2000.1237

Lala, R., Wood, D., & Baker, S. (2013). Validity of the UKCAT in applicant selection and predicting exam performance in UK dental students. *Journal of Dental Education*, *77*(9), 1159–1170. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/24002854

Laurence, C. O., Zajac, I. T., Lorimer, M., Turnbull, D. A., & Sumner, K. E. (2013). The impact of preparatory activities on medical school selection outcomes: a cross-sectional survey of applicants to the University of Adelaide Medical School in 2007. *BMC Medical Education*, *13*(1), 159. https://doi.org/10.1186/1472-6920-13-159

LeBlanc, V., Urbankova, A., Hadavi, F., & Lichtenthal, R. (2004). A preliminary study in using virtual reality to train dental students. *Journal of Dental Education*, *68*(3), 378–383.

Lederman, S J, & Klatzky, R. L. (1993). Extracting object properties through haptic exploration. *Acta Psychologica*, *84*(1), 29–40. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/8237454

Lederman, Susan J, & Klatzky, R. L. (1987). Hand movements: A window into haptic object recognition. *Cognitive Psychology*, *19*(3), 342–368. https://doi.org/10.1016/0010-0285(87)90008-9

Lee, H. J., Park, S. B., Park, S. C., Park, W. S., Ryu, S.-W., Yang, J. H., … Chae, G. B. (2016). Multiple mini-interviews as a predictor of academic achievements during the first 2 years of medical school. *BMC Research Notes*, *9*(1), 93. https://doi.org/10.1186/s13104-016-1866-0

Lemay, J.-F., Lockyer, J. M., Collin, V. T., & Brownell, A. K. W. (2007). Assessment of non-cognitive traits through the admissions multiple mini-interview. *Medical Education*, *41*(6), 573–579. https://doi.org/10.1111/j.1365-2923.2007.02767.x

Levine, A., DeMaria Jr., S., Schwartz, A., & Sim, A. (2013). *The Comprehensive Textbook of Healthcare Simulation*. New York, NY: Springer.

Lievens, F. (2013). Adjusting medical school admission: assessing interpersonal skills using situational judgement tests. *Medical Education*, *47*(2), 182–189. https://doi.org/10.1111/medu.12089

Lievens, F., Coetsier, P., De Fruyt, F., & De Maeseneer, J. (2002). Medical students' personality characteristics and academic performance: a five-factor model perspective. *Medical Education*, *36*(11), 1050–1056. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/12406265

Lievens, F., Peeters, H., & Schollaert, E. (2008). Situational judgment tests: a review of recent research. *Personnel Review*, *37*(4), 426–441. https://doi.org/10.1108/00483480810877598

Lin, D. T., Kannappan, A., & Lau, J. N. (2013). The Assessment of Emotional Intelligence Among Candidates Interviewing for General Surgery Residency. *Journal of Surgical Education*, *70*(4), 514–521. https://doi.org/10.1016/j.jsurg.2013.03.010

Litton-Hawes, E., MacLean, I. C., & Hines, M. H. (1976). An analysis of the communication process in the medical admissions interview. *Journal of Medical Education*, *51*(4), 332–334. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/1255691

Luck, O., Reitemeier, B., & Scheuch, K. (2000). Testing of fine motor skills in dental students. *European Journal of Dental Education : Official Journal of the Association for Dental Education in Europe*, *4*(1), 10–14. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/11168460

Lugassy, D., Levanon, Y., Pilo, R., Shelly, A., Rosen, G., Meirowitz, A., & Brosh, T. (2018). Predicting the clinical performance of dental students with a manual dexterity test. *PLOS ONE*, *13*(3), e0193980. https://doi.org/10.1371/journal.pone.0193980

Lumb, A. B., & Vail, A. (2004). Comparison of academic, application form and social factors in predicting early performance on the medical course. *Medical Education*, *38*(9), 1002–1005. https://doi.org/10.1111/j.1365-2929.2004.01912.x

Lundergan, W. P., Soderstrom, E. J., & Chambers, D. W. (2007). Tweezer dexterity aptitude of dental students. *Journal of Dental Education*, *71*(8), 1090–1097. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/17687091

Luqman, M. (2013). Relationship of academic success of medical students with motivation and pre-admission grades. *Journal of the College of Physicians and Surgeons--Pakistan : JCPSP*, *23*(1), 31–36. https://doi.org/01.2013/JCPSP.3136

Lynch, B., MacKenzie, R., Dowell, J., Cleland, J., & Prescott, G. (2009). Does the UKCAT predict Year 1 performance in medical school? *Medical Education*, *43*(12), 1203–1209. https://doi.org/10.1111/j.1365-2923.2009.03535.x

Lyons, C., Goldfarb, D., Jones, S. L., Badhiwala, N., Miles, B., Link, R., & Dunkin, B. J. (2013). Which skills really matter? proving face, content, and construct validity for a commercial robotic simulator. *Surgical Endoscopy*, *27*(6), 2020–2030. https://doi.org/10.1007/s00464-012-2704-7

Ma, L., Wang, B., Narayana, S., Hazeltine, E., Chen, X., Robin, D. A., … Xiong, J. (2010). Changes in regional activity are accompanied with changes in inter-regional connectivity during 4 weeks motor learning. *Brain Research*, *1318*, 64–76. https://doi.org/10.1016/j.brainres.2009.12.073

Maan, Z. N., Maan, I. N., Darzi, A. W., & Aggarwal, R. (2012). Systematic review of predictors of surgical performance. *British Journal of Surgery*, *99*(12), 1610–1621. https://doi.org/10.1002/bjs.8893

Maliha, S. G., Diaz-Siso, J. R., Plana, N. M., Torroni, A., & Flores, R. L. (2018). Haptic, Physical, and Web-Based Simulators: Are They Underused in Maxillofacial Surgery Training? *Journal of Oral and Maxillofacial Surgery*, *76*(11), 2424.e1-2424.e11. https://doi.org/10.1016/j.joms.2018.06.177

Mallikarjun, S. A., Tiwari, S., Sathyanarayana, S., & Devi, P. R. (2014). Haptics in periodontics. *Journal of Indian Society of Periodontology*, *18*(1), 112–113. https://doi.org/10.4103/0972-124X.128263

Mann, W. C. (1979). Interviewer scoring differences in student selection interviews. *The American Journal of Occupational Therapy : Official Publication of the American Occupational Therapy Association*, *33*(4), 235–239. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/443148

McAndrew, Ellis, J., & Valentine, R. A. (2017). Does a selection interview predict year 1 performance in dental school? *European Journal of Dental Education : Official Journal of the Association for Dental Education in Europe*, *21*(2), 108–112. https://doi.org/10.1111/eje.12188

McAndrew, R., & Ellis, J. (2012). An evaluation of the multiple mini-interview as a selection tool for dental students. *British Dental Journal*, *212*(7), 331–335. https://doi.org/10.1038/sj.bdj.2012.267

McAndrew, R., & Ellis, J. (2013). Applicants' perceptions on the multiple mini-interview process as a selection tool for dental and therapy and hygiene students. *British Dental Journal*, *215*(11), 565–570. https://doi.org/10.1038/sj.bdj.2013.1142

McClusky, D. A., Ritter, E. M., Lederman, A. B., Gallagher, A. G., & Smith, C. D. (2005). Correlation between perceptual, visuo-spatial, and psychomotor aptitude to duration of training required to reach performance goals on the MIST-VR surgical simulator. *The American Surgeon*, *71*(1), 13–20; discussion 20-1. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/15757051

McDougall, E. M. (2007). Validation of surgical simulators. *Journal of Endourology / Endourological Society*, *21*(3), 244–247. https://doi.org/10.1089/end.2007.9985

McGaghie, W. C., Issenberg, S. B., Petrusa, E. R., & Scalese, R. J. (2010). A critical review of simulation-based medical education research: 2003-2009. *Medical Education*, *44*, 50–63. https://doi.org/10.1111/j.1365-2923.2009.03547.x

McLaughlin, M. L., Hespanha, J. P., & Sukhatme, G. S. (2002). *Touch in virtual environments : haptics and the design of interactive systems*. Prentice Hall.

McManus, I. C., Dewberry, C., Nicholson, S., & Dowell, J. S. (2013). The UKCAT-12 study: educational attainment, aptitude test performance, demographic and socio-economic contextual factors as predictors of first year outcome in a cross-sectional collaborative study of 12 UK medical schools. *BMC Medicine*, *11*, 244. https://doi.org/10.1186/1741-7015-11-244

Mercer, A., Crotty, B., Alldridge, L., Le, L., & Vele, V. (2015). GAMSAT: A 10-year retrospective overview, with detailed analysis of candidates' performance in 2014. *BMC Medical Education*, *15*(1), 31. https://doi.org/10.1186/s12909-015-0316-3

Milburn, J. A., Khera, G., Hornby, S. T., Malone, P. S. C., & Fitzgerald, J. E. F. (2012). Introduction, availability and role of simulation in surgical education and training: review of current evidence and recommendations from the Association of Surgeons in Training. *International Journal of Surgery (London, England)*, *10*(8), 393–398. https://doi.org/10.1016/j.ijsu.2012.05.005

Minogue, J., & Jones, M. G. (2006). Haptics in Education: Exploring an Untapped Sensory Modality. *Review of Educational Research*, *76*(3), 317–348. https://doi.org/10.3102/00346543076003317

Mirghani, I., Mushtaq, F., Allsop, M. J., Al-Saud, L. M., Tickhill, N., Potter, C., … Manogue, M. (2018). Capturing differences in dental training using a virtual reality simulator. *European Journal of Dental Education*, *22*(1), 67–71. https://doi.org/10.1111/eje.12245

Miskry, T., Magos, T., & Magos, A. (2002). If you're no good at computer games, don't operate endoscopically! *Gynaecological Endoscopy*, *11*(6), 345–347. https://doi.org/10.1111/j.1365-2508.2002.00544.x

Mon-Williams, M., Mushtaq, F., Wilkie, R. M., Khambay, B., & Manogue, M. (2015). A three dimensional view of stereopsis in dentistry. *British Dental Journal*, *219*(10), 26–27. https://doi.org/10.1038/sj.bdj.XXX

Morris, J. G. (1999). The value and role of the interview in the student admissions process: a review. *Medical Teacher*, *21*(5), 473–481. https://doi.org/10.1080/01421599979149

Morris, R. W., & Pybus, D. A. (2007). "Orpheus" cardiopulmonary bypass simulation system. *The Journal of Extra-Corporeal Technology*, *39*(4), 228–233. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/18293807

Motola, I., Devine, L. A., Chung, H. S., Sullivan, J. E., & Issenberg, S. B. (2013). Simulation in healthcare education: a best evidence practical guide. AMEE Guide No. 82. *Medical Teacher*, *35*(10), e1511-30. https://doi.org/10.3109/0142159X.2013.818632

Mushtaq, F., Baraas, R. C., Al-Saud, L. M., Mirghani, I., van der Zee, C., Yates, E., … Manogue, M. (2016). Should prospective dental students be screened for colour vision deficits? *Bdj*, *221*(5), 227–228. https://doi.org/10.1038/sj.bdj.2016.633

Müürsepp, I., Aibast, H., Gapeyeva, H., & Pääsuke, M. (2012). Motor skills, haptic perception and social abilities in children with mild speech disorders. *Brain and Development*, *34*(2), 128–132. https://doi.org/10.1016/j.braindev.2011.02.002

Nunez, D. W., Taleghani, M., Wathen, W. F., & Abdellatif, H. M. A. (2012). Typodont versus live patient: predicting dental students' clinical performance. *Journal of Dental Education*, *76*(4), 407–413. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/22473552

Oosterveld, P., & ten Cate, O. (2004). Generalizability of a study sample assessment procedure for entrance selection for medical school. *Medical Teacher*, *26*(7), 635–639. https://doi.org/10.1080/01421590400004874

Oudshoorn, W. C. (2003). The utility of Canadian DAT Perceptual Ability and Carving Dexterity scores as predictors of psychomotor performance in first-year operative dentistry. *Journal* *of Dental Education*, *67*(11), 1201–1208. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/14650501

Overduin, S. A., D'avella, A., Carmena, J. M., & Bizzi, E. (2012). Microstimulation Activates a Handful of Muscle Synergies. *Neuron*, *76*, 1071–1077. https://doi.org/10.1016/j.neuron.2012.10.018

Owen, H. (2016). *Simulation in healthcare education: An extensive history*. *Simulation in Healthcare Education: An Extensive History*. https://doi.org/10.1007/978-3-319-26577-3

Oyler, D. R., Smith, K. M., Elson, E. C., Bush, H., & Cook, A. M. (2014). Incorporating multiple mini-interviews in the postgraduate year 1 pharmacy residency program selection process. *American Journal of Health-System Pharmacy : AJHP : Official Journal of the American Society of Health-System Pharmacists*, *71*(4), 297–304. https://doi.org/10.2146/ajhp130315

Papp, K. K., Polk, H. C., & Richardson, J. D. (1997). The relationship between criteria used to select residents and performance during residency. *American Journal of Surgery*, *173*(4), 326–329. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/9136789

Park, S. E., Susarla, S. M., & Massey, W. (2006a). Do admissions data and NBDE Part I scores predict clinical performance among dental students? *Journal of Dental Education*, *70*(5), 518–524. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/16687636

Park, S. E., Susarla, S. M., & Massey, W. (2006b). Do admissions data and NBDE Part I scores predict clinical performance among dental students? *Journal of Dental Education*, *70*(5), 518–524. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/16687636

Patel, R., Eaton, K. A., Garcia, A., Rincon, V., Adams, L., & Brooks, J. (2011). Factors Influencing Dental Practitioner Performance : A Summary of a Recent Literature Review. *Oral Health and Dental Management*, *10*(3), 119–130.

Patterson, F., Knight, A., Dowell, J., Nicholson, S., Cousans, F., & Cleland, J. (2016). How effective are selection methods in medical education? A systematic review. *Medical Education*, *50*, 36–60. https://doi.org/10.1111/medu.12817

Pau, A., Jeevaratnam, K., Chen, Y. S., Fall, A. A., Khoo, C., & Nadarajah, V. D. (2013). The Multiple Mini-Interview (MMI) for student selection in health professions training - a systematic review. *Medical Teacher*, *35*(12), 1027–1041. https://doi.org/10.3109/0142159X.2013.829912

Perry, S, Burrow, M., Leung, W., & Bridges, S. (2017). Simulation and curriculum design: a global survey in dental education. *Australian Dental Journal*, *62*(4), 453–463. https://doi.org/10.1111/adj.12522

Perry, Suzanne, Bridges, S. M., & Burrow, M. F. (2015). A review of the use of simulation in dental education. *Simulation in Healthcare : Journal of the Society for Simulation in Healthcare*, *10*(1), 31–37. https://doi.org/10.1097/SIH.0000000000000059

Peskun, C., Detsky, A., & Shandling, M. (2007). Effectiveness of medical school admissions criteria in predicting residency ranking four years later. *Medical Education*, *41*(1), 57–64. https://doi.org/10.1111/j.1365-2929.2006.02647.x

Peterson, S. (1974). The ADA chalk carving test. *Journal of Dental Education*, *38*(1), 11–15. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/4521029

Poldrack, R. A. (2015). Is "efficiency" a useful concept in cognitive neuroscience? *Developmental Cognitive Neuroscience*, *11*, 12–17. https://doi.org/10.1016/j.dcn.2014.06.001

Polyzois, I., Claffey, N., McDonald, A., Hussey, D., & Quinn, F. (2011). Can evaluation of a dental procedure at the outset of learning predict later performance at the preclinical level? A pilot study. *European Journal of Dental Education : Official Journal of the Association for Dental Education in Europe*, *15*(2), 104–109. https://doi.org/10.1111/j.1600-0579.2010.00647.x

Poole, P., Shulruf, B., Rudland, J., & Wilkinson, T. (2012). Comparison of UMAT scores and

GPA in prediction of performance in medical school: a national study. *Medical Education*, *46*(2), 163–171. https://doi.org/10.1111/j.1365-2923.2011.04078.x

Powis, D. (2015). Selecting medical students: An unresolved challenge. *Medical Teacher*, *37*(3), 252–260. https://doi.org/10.3109/0142159X.2014.993600

Puddey, I. B., & Mercer, A. (2014). Predicting academic outcomes in an Australian graduate entry medical programme. *BMC Medical Education*, *14*(1), 31. https://doi.org/10.1186/1472-6920-14-31

Pusic, M., Pecaric, M., & Boutis, K. (2011). How Much Practice Is Enough? Using Learning Curves to Assess the Deliberate Practice of Radiograph Interpretation. *Academic Medicine*, *86*(6), 731–736. https://doi.org/10.1097/ACM.0b013e3182178c3c

Qayumi, K., & Vancouver. (2010). Surgical Skills Lab: A Hub for Competency Training. *Journal of Investigative Surgery*, *23*(1), 48–56. https://doi.org/10.3109/08941930903469391

Randall, R, Davies, H., Patterson, F., & Farrell, K. (2006). Selecting doctors for postgraduate training in paediatrics using a competency based assessment centre. *Archives of Disease in Childhood*, *91*(5), 444–448. https://doi.org/10.1136/adc.2005.076653

Randall, Ray, Stewart, P., Farrell, K., & Patterson, F. (2006). Education Using an assessment centre to select doctors for postgraduate training in obstetrics and gynaecology Key content. https://doi.org/10.1576/toag.8.4.257.27277

Raybould, T. P., Raggard, D. C., & Norton, J. C. (1983). Psychomotor skills and technical ability in dental school. *Journal of Dental Education*, *47*(9), 594–598. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/6578251

Razack, S., Faremo, S., Drolet, F., Snell, L., Wiseman, J., & Pickering, J. (2009). Multiple mini-interviews versus traditional interviews: stakeholder acceptability comparison. *Medical Education*, *43*(10), 993–1000. https://doi.org/10.1111/j.1365-2923.2009.03447.x

Reis, J., Schambra, H. M., Cohen, L. G., Buch, E. R., Fritsch, B., Zarahn, E., … Krakauer, J. W. (2009). Noninvasive cortical stimulation enhances motor skill acquisition over multiple days through an effect on consolidation. *Proceedings of the National Academy of Sciences of the United States of America*, *106*(5), 1590–1595. https://doi.org/10.1073/pnas.0805413106

Reiter, H. I., Eva, K. W., Rosenfeld, J., & Norman, G. R. (2007). Multiple mini-interviews predict clerkship and licensing examination performance. *Medical Education*, *41*(4), 378–384. https://doi.org/10.1111/j.1365-2929.2007.02709.x

Ritter, E. M., McClusky, D. A., Gallagher, A. G., Enochsson, L., & Smith, C. D. (2006). Perceptual, visuospatial, and psychomotor abilities correlate with duration of training required on a virtual-reality flexible endoscopy simulator. *The American Journal of Surgery*, *192*(3), 379–384. https://doi.org/10.1016/j.amjsurg.2006.03.003

Roberts, C., Walton, M., Rothnie, I., Crossley, J., Lyon, P., Kumar, K., & Tiller, D. (2008). Factors affecting the utility of the multiple mini-interview in selecting candidates for graduate-entry medical school. *Medical Education*, *42*(4), 396–404. https://doi.org/10.1111/j.1365-2923.2008.03018.x

Roberts, C., Zoanetti, N., & Rothnie, I. (2009). Validating a multiple mini-interview question bank assessing entry-level reasoning skills in candidates for graduate-entry medicine and dentistry programmes. *Medical Education*, *43*(4), 350–359. https://doi.org/10.1111/j.1365-2923.2009.03292.x

Roberts, G. D., & Porter, A. M. (1989). Medical student selection--time for change: discussion paper. *Journal of the Royal Society of Medicine*, *82*(5), 288–291. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/2754684

Rohrich, R. J. (2006). "See one, do one, teach one": an old adage with a new twist. *Plastic and Reconstructive Surgery*, *118*(1), 257–258. https://doi.org/10.1097/01.prs.0000233177.97881.85

Rose, J., Buchanan, J., & Sarrett, D. (1999). The DentSim system. *Journal of Dental Education*, *63*, 421–423.

Rosen, J. M., Long, S. A., McGrath, D. M., & Greer, S. E. (2009). Simulation in Plastic Surgery Training and Education: The Path Forward. *Plastic and Reconstructive Surgery*, *123*(2), 729–738. https://doi.org/10.1097/PRS.0b013e3181958ec4

Rosenbaum, D A, Kenny, S. B., & Derr, M. A. (1983). Hierarchical control of rapid movement sequences. *Journal of Experimental Psychology. Human Perception and Performance*, *9*(1), 86–102. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/6220126

Rosenbaum, David A, Cohen, R. G., Jax, S. A., Weiss, D. J., & Van Der Wel, R. (2007). The problem of serial order in behavior: Lashley's legacy. https://doi.org/10.1016/j.humov.2007.04.001

Rosenberg, J., Grantcharov, T. P., Bardram, L., & Funch-Jensen, P. (2003). Impact of hand dominance, gender, and experience with computer games on performance in virtual reality laparoscopy. *Surgical Endoscopy*, *17*(7), 1082–1085. https://doi.org/10.1007/s00464-002-9176-0

Rosenfeld, J. M., Reiter, H. I., Trinh, K., & Eva, K. W. (2008). A Cost Efficiency Comparison Between The Multiple Mini-Interview and Traditional Admissions Interviews. *Advances in Health Sciences Education*, *13*(1), 43–58. https://doi.org/10.1007/s10459-006-9029-z

Rostom, H., Watson, R., & Leaver, L. (2013). Situational judgement tests: the role of coaching. *Medical Education*, *47*(2), 219. https://doi.org/10.1111/medu.12070

Ruscio, J., & Roche, B. (2012). Determining the number of factors to retain in an exploratory factor analysis using comparison data of known factorial structure. *Psychological Assessment*, *24*(2), 282–292. https://doi.org/10/dhj3zz

Sadnicka, A., Kornysheva, K., Rothwell, J. C., & Edwards, M. J. (2017). A unifying motor control framework for task-specific dystonia. *Nature Reviews Neurology*, *14*(2), 116–124. https://doi.org/10.1038/nrneurol.2017.146

Sakai, K., Kitaguchi, K., & Hikosaka, O. (2003). Chunking during human visuomotor sequence learning. *Experimental Brain Research*, *152*(2), 229–242. https://doi.org/10.1007/s00221-003-1548-8

Salgado, J., Grantcharov, T. P., Papasavas, P. K., Gagne, D. J., & Caushaj, P. F. (2009). Technical skills assessment as part of the selection process for a fellowship in minimally invasive surgery. *Surgical Endoscopy*, *23*(3), 641–644. https://doi.org/10.1007/s00464-008-0033-7

Salvatori, P. (2001). Reliability and validity of admissions tools used to select students for the health professions. *Advances in Health Sciences Education : Theory and Practice*, *6*(2), 159–175. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/11435766

Sandow, P. L., Jones, A. C., Peek, C. W., Courts, F. J., & Watson, R. E. (2002). Correlation of admission criteria with dental school performance and attrition. *Journal of Dental Education*, *66*(3), 385–392. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/11936229

Schaefer, J. J., Vanderbilt, A. A., Cason, C. L., Bauman, E. B., Glavin, R. J., Lee, F. W., & Navedo, D. D. (2011). Literature review: instructional design and pedagogy science in healthcare simulation. *Simulation in Healthcare : Journal of the Society for Simulation in Healthcare*, *6 Suppl*, S30-41. https://doi.org/10.1097/SIH.0b013e31822237b4

Schlaug, G. (2001). The brain of musicians. A model for functional and structural adaptation. *Annals of the New York Academy of Sciences*, *930*, 281–299. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/11458836

Schmidt, F., & Hunter, J. E. (1998). The Validity and Utility of Selection Methods in Personnel Psychology: Practical and Theoretical Implications of 85 Years of Research Findings. *Psychological Bulletin*, *124*(2), 262–274.

Schultheis, M. T., & Rizzo, A. A. (2001). The application of virtual reality technology in rehabilitation. *Rehabilitation Psychology*, *46*(3), 296–311. https://doi.org/10.1037/0090-5550.46.3.296

Sequeira, G., Keogh, J. W., & Kavanagh, J. J. (2012). Resistance training can improve fine manual dexterity in essential tremor patients: a preliminary study. *Archives of Physical Medicine and Rehabilitation*, *93*(8), 1466–1468. https://doi.org/10.1016/j.apmr.2012.02.003

Shahriari-Rad, A. (2013). The Extent of Virtual Reality Simulation Enhancing Assessment of Psychomotor Clinical Skills. In T. Bastiaens & G. Marks (Eds.), *Proceedings of E-Learn: World Conference on E-Learning in Corporate, Government, Healthcare, and Higher Education 2013* (pp. 410–415). Las Vegas, NV, USA: Association for the Advancement of Computing in Education (AACE).

Shellito, J. L., Osland, J. S., Helmer, S. D., & Chang, F. C. (2010). American Board of Surgery examinations: can we identify surgery residency applicants and residents who will pass the examinations on the first attempt? *American Journal of Surgery*, *199*(2), 216–222. https://doi.org/10.1016/j.amjsurg.2009.03.006

Shire, K. A., B Hill, L. J., Snapp-Childs, W., Bingham, G. P., Kountouriotis, G. K., Barber, S., & Mon-Williams, M. (2016). Robot Guided "Pen Skill" Training in Children with Motor Difficulties. https://doi.org/10.1371/journal.pone.0151354

Shmuelof, L., Krakauer, J. W., & Mazzoni, P. (2012). How is a motor skill learned? Change and invariance at the levels of task success and trajectory control. *Journal of Neurophysiology*, *108*(2), 578–594. https://doi.org/10.1152/jn.00856.2011

Simon, E., Walsh, K., Paterson-Brown, F., & Cahill, D. (2015). Does a high ranking mean success in the Situational Judgement Test? *The Clinical Teacher*, *12*(1), 42–45. https://doi.org/10.1111/tct.12239

Singapogu, R., Burg, T., Burg, K. J. L., Smith, D. E., & Eckenrode, A. H. (2014). A perspective on the role and utility of haptic feedback in laparoscopic skills training. *Critical Reviews in Biomedical Engineering*, *42*(3–4), 293–318. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/25597241

Small, S. D., Wuerz, R. C., Simon, R., Shapiro, N., Conn, A., & Setnik, G. (1999). Demonstration of high-fidelity simulation team training for emergency medicine. *Academic Emergency Medicine : Official Journal of the Society for Academic Emergency Medicine*, *6*(4), 312–323. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/10230983

Smith, M. A., & Shadmehr, R. (2005). Intact ability to learn internal models of arm dynamics in Huntington's disease but not cerebellar degeneration. *Journal of Neurophysiology*, *93*(5), 2809–2821. https://doi.org/10.1152/jn.00943.2004

Sohmura, T., Hojo, H., Nakajima, M., Wakabayashi, K., Nagao, M., Iida, S., … Takahashi, J. (2004). Prototype of simulation of orthognathic surgery using a virtual reality haptic device. *International Journal of Oral and Maxillofacial Surgery*, *33*(8), 740–750. https://doi.org/10.1016/j.ijom.2004.03.003

Spratley, M. H. (1990). Aptitude testing and the selection of dental students. *Australian Dental Journal*, *35*(2), 159–168. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/2189383

Stanley, J., & Krakauer, J. W. (2013). Motor skill depends on knowledge of facts. *Frontiers in Human Neuroscience*, *7*, 503. https://doi.org/10.3389/fnhum.2013.00503

Suddick, R. P., Yancey, J. M., Devine, S., & Wilson, S. (1982). Field dependence-independence and dental students' clinical performance. *Journal of Dental Education*, *46*(4), 227–232. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/6950965

Suebnukarn, S., Phatthanasathiankul, N., Sombatweroje, S., Rhienmora, P., & Haddawy, P. (2009). Process and outcome measures of expert/novice performance on a haptic virtual reality system. *Journal of Dentistry*, *37*(9), 658–665. https://doi.org/10.1016/j.jdent.2009.04.008

Suksudaj, N., Townsend, G. C., Kaidonis, J., Lekkas, D., & Winning, T. A. (2012). Acquiring psychomotor skills in operative dentistry: do innate ability and motivation matter? *European Journal of Dental Education*, *16*(1), e187–e194. https://doi.org/10.1111/j.1600-0579.2011.00696.x

Swanson, D. B., Sawhill, A., Holtzman, K. Z., Bucak, S. D., Morrison, C., Hurwitz, S., & DeRosa, G. P. (2009). Relationship Between Performance on Part I of the American Board of Orthopaedic Surgery Certifying Examination and Scores on USMLE Steps 1 and 2. *Academic Medicine*, *84*(Supplement), S21–S24. https://doi.org/10.1097/ACM.0b013e3181b37fd2

Tektas, O., Fiessler, C., Mayr, A., Neuhuber, W., & Paulsen, F. (2013). Correlation of high school exam grades with study success at a German medical school. *Journal of Contemporary Medical Education*, *1*(3), 157. https://doi.org/10.5455/jcme.20130311114703

Telgen, S., Parvin, D., & Diedrichsen, J. (2014). Mirror reversal and visual rotation are learned and consolidated via separate mechanisms: recalibrating or learning de novo? *The Journal of Neuroscience : The Official Journal of the Society for Neuroscience*, *34*(41), 13768–13779. https://doi.org/10.1523/JNEUROSCI.5306-13.2014

Till, H., Myford, C., & Dowell, J. (2013). Improving student selection using multiple mini-interviews with multifaceted Rasch modeling. *Academic Medicine : Journal of the Association of American Medical Colleges*, *88*(2), 216–223. https://doi.org/10.1097/ACM.0b013e31827c0c5d

Toni, I., Krams, M., Turner, R., & Passingham, R. E. (1998). The Time Course of Changes during Motor Sequence Learning: A Whole-Brain fMRI Study. *NeuroImage*, *8*(1), 50–61. https://doi.org/10.1006/nimg.1998.0349

Towers, A., Field, J., Stokes, C., Maddock, S., & Martin, N. (2019). A scoping review of the use and application of virtual reality in pre-clinical dental education. *British Dental Journal*, *226*(5), 358–366. https://doi.org/10.1038/s41415-019-0041-0

Tresilian, J. (University of W. (2012). *Sensorimotor, Control & Learning*.

Trost, G., Nauels, H., & Klieme, E. (1998). The Relationship between Different Criteria for Admission to Medical School and Student Success. *Assessment in Education: Principles, Policy & Practice*, *5*(2), 247–254. https://doi.org/10.1080/0969594980050206

Tseng, Y., Diedrichsen, J., Krakauer, J. W., Shadmehr, R., & Bastian, A. J. (2007). Sensory Prediction Errors Drive Cerebellum-Dependent Adaptation of Reaching. *Journal of Neurophysiology*, *98*(1), 54–62. https://doi.org/10.1152/jn.00266.2007

Turner, N. S., Shaughnessy, W. J., Berg, E. J., Larson, D. R., & Hanssen, A. D. (2006). A Quantitative Composite Scoring Tool for Orthopaedic Residency Screening and Selection. *Clinical Orthopaedics and Related Research*, *PAP*. https://doi.org/10.1097/01.blo.0000224042.84839.44

Ungerleider, L. G., Doyon, J., & Karni, A. (2002). Imaging brain plasticity during motor skill learning. *Neurobiology of Learning and Memory*, *78*(3), 553–564. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/12559834

Urbankova, A. (2010). Impact of computerized dental simulation training on preclinical operative dentistry examination scores. *Journal of Dental Education*, *74*(4), 402–409.

Urbankova, Alice, Eber, M., & Engebretson, S. P. (2013). A complex haptic exercise to predict preclinical operative dentistry performance: a retrospective study. *Journal of Dental Education*, *77*(11), 1443–1450. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/24192409

Urbankova, Alice, & Engebretson, S. P. (2011). The use of haptics to predict preclinic operative dentistry performance and perceptual ability. *Journal of Dental Education*, *75*(12), 1548–1557. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/22184593

Urlings-Strop, L. C., Stegers-Jager, K. M., Stijnen, T., & Themmen, A. P. N. (2013). Academic and non-academic selection criteria in predicting medical school performance. *Medical Teacher*, *35*(6), 497–502. https://doi.org/10.3109/0142159X.2013.774333

Van Herzeele, I., O'Donoghue, K. G. L., Aggarwal, R., Vermassen, F., Darzi, A., & Cheshire, N. J. W. (2010). Visuospatial and psychomotor aptitude predicts endovascular performance of inexperienced individuals on a virtual reality simulator. *Journal of Vascular Surgery*, *51*(4), 1035–1042. https://doi.org/10.1016/j.jvs.2009.11.059

Velayo, B. C., Stark, P. C., Eisen, S. E., & Kugel, G. (2014). Using dental students' preclinical performance as an indicator of clinical success. *Journal of Dental Education*, *78*(6), 823–828. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/24882767

Vervoorn, J., Wesselink, P. R., Cox, M. J., Quinn, B., & Shahriari-Rad, A. (2015). Evidence from the Dental Education Communities: review of the field. In *Symposium on Technology Enhanced Learning to Enrich Dental Education at the International Association for Dental Research Conference* (pp. 1–11). Boston.

Vozenilek, J., Huff, J. S., Reznek, M., & Gordon, J. A. (2004). See One, Do One, Teach One: Advanced Technology in Medical Education. *Academic Emergency Medicine*, *11*(11), 1149–1154. https://doi.org/10.1197/j.aem.2004.08.003

Walcott, A. M., Knight, G. W., & Charlick, R. E. (1986). Waxing tests as predictors of students' performance in preclinical dentistry. *Journal of Dental Education*, *50*(12), 716–721. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/3465775

Waldman, K. B., Macdonald, G., & Wilson, S. G. (1995). The relationship between standardized psychomotor tests and basic clinical dental hygiene skills. *Journal of Dental Hygiene : JDH / American Dental Hygienists' Association*, *69*(4), 163–168. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/10483412

Walker, J. D., Killip, D. E., & Fuller, J. L. (1985). The significance of the admission interview in predicting students' performance in dental school. *Journal of Medical Education*, *60*(7), 569–571. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/4009676

Wanzel, K. R., Hamstra, S. J., Caminiti, M. F., Anastakis, D. J., Grober, E. D., & Reznick, R. K. (2003). Visual-spatial ability correlates with efficiency of hand motion and successful surgical performance. *Surgery*, *134*(5), 750–757. https://doi.org/10.1016/S0039

Waras, W. (2016). Motor Control and Learning: A. Behavioral Emphasis. Richard A. Schmidt. Champaign, Illinois: Human Kinetics Publishers, Inc. 1998. *Teknologi Dan Kejuruan*, *17*(2). https://doi.org/10.17977/tk.v17i2.7290

Ward, S T, Hancox, A., Mohammed, M. A., Ismail, T., Griffiths, E. A., Valori, R., & Dunckley, P. (2017). The learning curve to achieve satisfactory completion rates in upper GI endoscopy: an analysis of a national training database. *Gut*, *66*(6), 1022–1033. https://doi.org/10.1136/gutjnl-2015-310443

Ward, Stephen Thomas, Mohammed, M. A., Walt, R., Valori, R., Ismail, T., & Dunckley, P. (2014). An analysis of the learning curve to achieve competency at colonoscopy using the JETS database. *Gut*, *63*(11), 1746–1754. https://doi.org/10.1136/gutjnl-2013-305973

Watson, A. H. D. (2006). What can studying musicians tell us about motor control of the hand? *Journal of Anatomy*, *208*(4), 527–542. https://doi.org/10.1111/j.1469-7580.2006.00545.x

Weine, F. S., Kelly, R. F., & Lio, P. J. (1975). The effect of preparation procedures on original canal shape and on apical foramen shape. *Journal of Endodontics*, *1*(8), 255–262. https://doi.org/10.1016/S0099-2399(75)80037-9

Werz, S. M., Zeichner, S. J., Berg, B.-I., Zeilhofer, H.-F., & Thieringer, F. (2018). 3D Printed Surgical Simulation Models as educational tool by maxillofacial surgeons. *European Journal of Dental Education*, *22*(3), e500–e505. https://doi.org/10.1111/eje.12332

Westerman, G. H., Grandy, T. G., Combs, C. G., & Turner, C. H. (1989). Personality variables as predictors of performance for first-year dental students. *Journal of Dental Education*, *53*(4), 233–237. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/2703580

Wierinck, E., Puttemans, V., & van Steenberghe, D. (2006). Effect of reducing frequency of augmented feedback on manual dexterity training and its retention. *Journal of Dentistry*, *Oct;34*(9), 641–647.

Wierinck, E. R., Puttemans, V., Swinnen, S. P., & van Steenberghe, D. (2007). Expert performance on a virtual reality simulation system. *Journal of Dental Education*, *71*(6), 759–766. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/17554093

Willaert, W. I. M., Aggarwal, R., Van Herzeele, I., Cheshire, N. J., & Vermassen, F. E. (2012). Recent Advancements in Medical Simulation: Patient-Specific Virtual Reality Simulation. *World Journal of Surgery*, *36*(7), 1703–1712. https://doi.org/10.1007/s00268-012-1489-0

Williams & Monsma. (2006). *Assessment of gross motor development*.

Wilson, S., Suddick, R. P., Shay, J. S., & Hustmyer, F. E. (1981). Correlations of Scores on Embedded Figures and Mirror Tracing with Preclinical Technique Grades and Pmat Scores of Dental Students. *Perceptual and Motor Skills*, *53*(1), 31–35. https://doi.org/10.2466/pms.1981.53.1.31

Wolpert, D. M., Diedrichsen, J., & Flanagan, J. R. (2011). Principles of sensorimotor learning. *Nature Reviews Neuroscience*, *12*(12), 739–751. https://doi.org/10.1038/nrn3112

Won, A. S., Bailey, J., Bailenson, J., Tataru, C., Yoon, I. A., & Golianu, B. (2017). Immersive Virtual Reality for Pediatric Pain. *Children (Basel, Switzerland)*, *4*(7). https://doi.org/10.3390/children4070052

Wood, W. W. (1979). Grade averages and DAT scores as predictors of performance in dental school. *Journal of Dental Education*, *43*(12), 630–632. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/290664

Wouters, A., Bakker, A. H., van Wijk, I. J., Croiset, G., & Kusurkar, R. A. (2014). A qualitative analysis of statements on motivation of applicants for medical school. *BMC Medical Education*, *14*(1), 200. https://doi.org/10.1186/1472-6920-14-200

Wright, S. R., & Bradley, P. M. (2010). Has the UK Clinical Aptitude Test improved medical student selection? *Medical Education*, *44*(11), 1069–1076. https://doi.org/10.1111/j.1365-2923.2010.03792.x

Wu, F., Chen, X., Lin, Y., Wang, C., Wang, X., Shen, G., … Heng, P.-A. (2014). A virtual training system for maxillofacial surgery using advanced haptic feedback and immersive workbench. *The International Journal of Medical Robotics and Computer Assisted Surgery*, *10*(1), 78–87. https://doi.org/10.1002/rcs.1514

Wymbs, N. F., & Grafton, S. T. (2015). The Human Motor System Supports Sequence-Specific Representations over Multiple Training-Dependent Timescales. *Cerebral Cortex*, *25*(11), 4213–4225. https://doi.org/10.1093/cercor/bhu144

Yarrow, K., Brown, P., & Krakauer, J. W. (2009). Inside the brain of an elite athlete: the neural processes that support high achievement in sports. *Nature Reviews Neuroscience*, *10*(8), 585–596. https://doi.org/10.1038/nrn2672

Yates, J., & James, D. (2010). The value of the UK Clinical Aptitude Test in predicting pre-clinical performance: a prospective cohort study at Nottingham Medical School. *BMC Medical Education*, *10*(1), 55. https://doi.org/10.1186/1472-6920-10-55

Yates, J., & James, D. (2013). The UK Clinical Aptitude Test and clinical course performance at Nottingham: a prospective cohort study. *BMC Medical Education*, *13*, 32. https://doi.org/10.1186/1472-6920-13-32

Yeo, G. B., & Neal, A. (2004). A Multilevel Analysis of Effort, Practice, and Performance: Effects; of Ability, Conscientiousness, and Goal Orientation. *Journal of Applied Psychology*, *89*(2), 231–247. https://doi.org/10.1037/0021-9010.89.2.231

Yu, H., Cheng, J., Cheng, A. H., & Shen, S. G. (2011). Preliminary Study of Virtual Orthognathic Surgical Simulation and Training. *Journal of Craniofacial Surgery*, *22*(2), 648–651. https://doi.org/10.1097/SCS.0b013e318207f2e8

Ziv, A., Rubin, O., Moshinsky, A., Gafni, N., Kotler, M., Dagan, Y., … Mittelman, M. (2008). MOR: a simulation-based assessment centre for evaluating the personal and interpersonal qualities of medical school candidates. *Medical Education*, *42*(10), 991–998. https://doi.org/10.1111/j.1365-2923.2008.03161.x

# Appendices

## **Appendix A -** Chapter 4 Assessment of Multiple Mini Interview (MMI) selection process

## A.1 Marking criteria for MMI's stations

| Station | Question | Scale used |
|---|---|---|
| **Station1**<br><br>**Memory** | The number of objects remembered by the candidate? | Scale from 0 to 20. |
| | How accurately they described objects 1, 2 and 3? | Ratings are on a sliding scale where 1=vague and 4=very accurately (vague/ basic/ some detail/ very accurately). |
| | Confidence of the candidates while performance. | Ratings are on sliding scale where 1=not at all confidently and 4=very confident (not at all confidently/ slightly hesitant/ confident/ very confident). |
| | Global rating<br><br>How happy the examiner would accept this candidate? | Ratings with 1=not happy at all and 4=very happy indeed (not happy at all/ quite unhappy/ happy/ very happy indeed). |
| **Station 2, 5 and 7**<br><br>**Ethics, Insight and Interpretation** | Candidate performance on the task | Rating with a scale of 1 to 4 with 1=very poor and 4=excellent (very poor/ poor/ good/ excellent). |

| | | |
|---|---|---|
| | Global rating | Rating on a scale of 1 to 4 with 1=not happy at all and 4=very happy indeed (not happy at all/ quite unhappy/ happy/ very happy indeed). |
| **Station 3**<br>**Presentation** | Preparation | Rated with a scale of 0 to 2 with 0=inadequate, 1= partially met criteria and 2=performed fully, adequately and completely. |
| | The presentation structure contained | Rated with a scale of 0 to 2 with 0=inadequate, 1= partially met criteria and 2=performed fully, adequately and completely. |
| | Content of the presentation | Rated with a scale of 0 to 2 with 0=inadequate, 1= partially met criteria and 2=performed fully, adequately and completely. |
| | Communication | Rated with a scale of 0 to 2 with 0=inadequate, 1= partially met criteria and 2=performed fully, adequately and completely. |
| | Understanding | Rated with a scale of 0 to 2 with 0=inadequate, 1= partially met criteria and 2=performed fully, adequately and completely. |

| | | |
|---|---|---|
| | Global rating | Rating on a scale of 1 to 4 with 1=not happy at all and 4=very happy indeed (not happy at all/ quite unhappy/ happy/ very happy indeed). |
| **Station 4**<br>**Origami** | Last correctly completed stage of the paper shape | A scale of letters from A to S was provided to the examiner and each letter corresponded to a level or stage of the task which was shown in a series of pictures and which would be the score they achieved for reaching that stage |
| | Global rating | Rating on a scale of 1 to 4 with 1=not happy at all and 4=very happy indeed (not happy at all/ quite unhappy/ happy/ very happy indeed). |
| **Station 6**<br>**Communication** | Candidate performance on the task | Rating is on a scale of 1 to 4 with 1=very poor and 4=excellent<br>(poor/ below average/ good/ excellent). |
| | Global rating by examiner | Rating on a scale of 1 to 4 with 1=not happy at all and 4=very happy indeed |

| | | |
|---|---|---|
| | | |
| | Global rating by an actor | Rating on a scale of 1 to 5 with 1=strongly disagree and 5=strongly agree (strongly disagree/ disagree/ ambivalent/ agree/ strongly agree). |
| **Station 8**<br>**Tangram** | Initial letter of shape attempted with | R=Rabbit, B=Boat, H=House, M=Mr Bean, G=Goose, V=Vulture, S=Shark and A=Archway. |
| | Completion of shape | Rating on a scale of 1 to 4 using the marking criteria where 1 is incomplete and 4 is complete and accurate (incomplete/ major errors/ minor errors/ accurate). |
| | Objective observers rating | Rating on a scale of 1 to 4 where 1=poor and 4=excellent (poor/ below average/ good/ excellent). |
| | Global rating by an observer | Rating on a scale of 1 to 4 with 1=not happy at all and 4=very happy indeed |

| | | |
|---|---|---|
| | | (not happy at all/ quite unhappy/ happy/ very happy indeed). |
| | Student examiners ratings | Rating on a scale of 1 to 4 where 1=poor and 4=excellent (poor/ below average/ good/ excellent). |
| | Global rating by student examiners | Ratings on how happy the examiner would accept this candidate on a scale of 1 to 4 with 1=not happy at all and 4=very happy indeed (not happy at all/ quite unhappy/ happy/ very happy indeed). |
| **For station 1, 2, 3, 4, 5, 6, 7 and 8 a composite score has been calculated.** | | |
| **Station 9 and 10**<br>**CKAT and Simodont** | Performance on the task | Percentage score. |
| **For station 9 a composite score has been calculated, however, for the station 10, two parameters contributed to the calculation of a composite measure to take into account overall performance: target and error scores (target score-** | | |

**[(sum of leeway's/2) + (sum of containers*20)]). The target and error scores (sum of leeway, leeway bottom, leeway side, container bottom and container side) were all measured in percentages.**

# **Appendix B -** Chapter 6 MMIs as a predictor of undergraduate dental performance

## B.1 Information Booklet

**What makes a good dentist?**

**...and how you can help us find the answer.**

**student information pack**

**FACULTY OF MEDICINE AND HEALTH, UNIVERSITY OF LEEDS**

**This is a collaborative research project between the Schools of Dentistry, Psychology and Mechanical Engineering at the University of Leeds.**

**The research team includes Israa Mirghani, Faisal Mushtaq, Peter Culmer, Andrew Keeling, Mark Mon-Williams and Michael Manogue.**
**www.leeds.ac.uk/paclab**

**2016**

**Photographs by Tim Zoltie. Design by Cecilie Osnes**

**Introduction**

We are contacting you because researchers at the School of Dentistry, in collaboration with psychologists and engineers, are about to start an exciting new research project. The project sets out to understand the fundamental, operative skills necessary for safe and effective dentistry and aims to shed light on the core characteristics necessary to be a good dentist. In this information pack we provide you with an introduction to the project, how you can help us, and the implications of this work on you and your peers. As you are aware, the dental training process can be long and costly, thus being able to identify individuals with necessary aptitude for the profession is essential for both trainee and training institutions alike. Over the past two decades, a number of studies have been conducted to see whether it is possible to predict future dental performance and ability. A Level Grades, aptitude tests, interviews and manual dexterity tests have all been studied in order to predict performance of the students' future success. Al- though these approaches have been interesting, the results have been inconclusive. We aim to address this gap in our knowledge by embarking on an ambitious project that uses state-of-the-art research tools and powerful statistical analysis techniques to understand the underlying relationships between these kinds of tests and actual, real world dental performance. In order for us to achieve this ambitious goal (there are many different ways to be a "good" dentist!) we need to use a lot of the data that are already being collected at the School of Dentistry as part of your studies.

**Objective**

The aim of our study is to examine if the tests you did at the Multi Mini Interviews have any ability to predict dental surgery ability by tracking clinical, lab and examination performance over the course of the dentistry degree.

**The MMIs**

The Multi Mini Interviews (MMIs) -- the tests you did before receiving an offer from us for a place on the degree programme-- are a relatively new interview format that use short independent assessments, typically in a timed circuit. It is used to assess non cognitive qualities such as cultural sensitivity, maturity, teamwork, empathy and reliability. It provides admissions teams with comprehensive information about the suitability of candidates. MMIs are thought to be better predictors of academic performance than a traditional interview format. For the School of Dentistry, MMIs provide a unique opportunity to assess candidates on different skills necessary for the practice of dentistry; skills that cannot easily be assessed in an interview or an application form. We are interested in investigating the predictive relationship between performance on the MMI under- graduate selection process and surgical ability in undergraduate dental students.

**The Study**

This study is a longitudinal study which can be divided into three parts:

1- Data from MMIs
2- Tracking
3- Outcome

**Data from MMIs**

Each station assesses an essential skill required for being a dentist. Below are the skills that have been tested:-

Motor skills

Ethical awareness and reasoning

Communication skills

Analytical and data interpretation skills

Observation and memory skills

Ability to follow instructions

Empathy skills

Insight into issues

We will look into each station and what skill it meant to assess and obtain the score for the specific station. Scores for all the stations will be collected and analysed.

**Tracking**

This is the second part of the study, we will be tracking your clinical lab and examination performance over the duration of your study. Below is a list outlining the data that we will be tracking for each year:

| **Year** | **Tracking Data** |
|---|---|
| Year1 | Induction on Simodont |
| Year2 | CSA results |
| Year 3 | CSB results |
| Year4 | Crown test and OSCE |
| Year 5 | Overall performance |

**Outcome**

This is the third and the most important part of the study. In this part, data from the first part will be used in conjunction with the second part of the study and here the data will be analysed to explore the predictive value of MMI on subsequent performance in the dentistry programme.

**Potential outcomes from this research**

Our main aim is to understand the factors that contribute to making a good dentist. More specifically, we will be able to assess and evaluate the MMls as a measuring tool for the selection process of undergraduate dental students at the University of Leeds School of Dentistry. It will provide the School with valuable evaluation of their MMls and ways of improving them. It will help us explore and discover new prediction tools for dental performance, thus enabling the School of Dentistry to select candidates with the necessary aptitudes, who will be able to excel in their studies and the profession. It allow us to identify individuals who are likely to need extra support at an early stage. It will help in decreasing the number of dropouts, thus, saving cost and time for the student and the institution.

**What do I need to do?**

You do not need to do anything right now. The data will be automatically collected and before we are able to analyse it, it will be anonymised. Every participant will be allocated a unique six digit study number. If you do not wish to take part in this study you can chose to withdraw. Your data will be withdrawn with- out needing to give any reason and this will have no consequences to your academic studies in any way.

**Frequently asked Questions**

*Can I withdraw?*

Yes, of course. You can withdraw from the study at any time without needing to give a reason and this will have no consequences on your academic studies. Withdrawal is also very easy: you do not need to contact a member of staff, you can simply use  the following link, enter your student ID and your data will be removed from any further analysis: https://leeds.onlinesurveys.ac.uk/prediction-consent

*What affect will withdrawal have on me?*

Withdrawal will have absolutely no consequences on your academic studies in anyway.

# B.2 Details of assessment modules (Year 1 to Year 4)

## B.2.1 Table 1 Year 1 MChD /BChD Assessment

| Credits | Modules | Assessments | Length | % of module |
|---|---|---|---|---|
| 20 | Personal & Professional Development 1 | Dental Treatment Report | 600 words | 30% |
| | | Assignment on Memory and Learning | 800 words | 40% |
| | | Group work and presentation | | 30% |
| 20 | Health Promotion | Individual project report | 1500 words | 50% |
| | | Written exam | 1 hour | 50% |
| 20 | Introduction to the Oral Environment | Spotter | 1 hour | 10% |
| | | Written exam | 1 hour | 90% |
| 30 | Oral Disease, Defence & Repair 1 | Written Exam | 2.5 hours | 100% |
| 20 | Anxiety & Pain Management | Written exam | 1 hour | 70% |
| | | Spotter | 1 hour | 30% |
| 10 | Clinical Practice 1 | Scenario written exam | 1 hr | 100% |

## B.2.2 Table 2 Year 2 MChD /BChD Assessment

| Credits | Modules | Assessments | Length | % of module |
|---|---|---|---|---|
| 60 | Clinical Skills A | Practical Spotter test | 2 hrs | 50% |
| | | Written exam | 2 hrs | 50% N/C |
| 10 | Social Sciences Related to Dentistry | Written exam | 1.5 hrs | 100% |
| 10 | Intro to Biomedical Sciences | Written exam | 2 hrs | 100% |
| 20 | Personal & Professional Development 2 | Contribution to poster presentation | n/a | 60% |
| | | Essay | 1000 words | 40% |
| 15 | Clinical Practice 2 | Scenario written exam | 1 hr | 100% |

## B.2.3 Table 3 Year 3 MChD/BChD Assessment

| Credits | Year 3 | Assessments | Length | % of module |
|---|---|---|---|---|
| 20 | Illness & Wellbeing | Written exam | 2 hrs | 100% |
| 20 | UG Projects | Portfolio: Research strategy & Medline search | | 10% |
| | | Portfolio: CASP | | 20% |
| | | Portfolio: Annotated Bibliography | | 20% |
| | | Written exam | 1 hr | 50% |
| 50 | Clinical Skills B | Crown test – MCC & FVC | | 50% |
| | | Exam | 2 hrs | 50% |
| 10 | Child Centred Dentistry 1 | Written exam | 1 hr | 100% |
| 10 | Personal & Professional Development 3 | Presentations (all day) | | 40% |
| | | Written exam | 1 hr | 60% |
| 20 | Clinical Practice 3 | Case presentation report | | 20% |
| | | Scenario written exam | 1 hr | 40% |
| | | OSCE | 2 days | 40% N/C |

## B.2.4 Table 4 Year 4 MChD/BChD Assessment

| Credits | Year 4 | Assessments | Length | % of module |
|---|---|---|---|---|
| 30 | Clinical Medical Science 1 | LDI Clinical Diary | | 40% |
| | | Written exam | 1.5 hrs | 60% |
| 35 | Complex Adult Dentistry | Spotter | 1.5 hrs | 50% |
| | | Exam | 1.5 hrs | 50% |
| 10 | Child Centred Dentistry | Ortho exam | 1 hr | 50% |
| | | Paeds exam | 1 hr | 50% |
| 10 | Personal & Professional Development 4 | Reflective assignment | 1500 words | 100% |
| 40 | Clinical Practice 4 | Perio case presentation | | 10% |
| | | Scenario paper written exam | 2 hrs | 40% |
| | | OSCE Parts 1 & 2 | | 50% |
| 20 | Final Year Project | Project Proposal | 1500 words | 20% |
| | | Supervisor's mark | | 10% |
| | | Final report | 4000 words | 70% |

# Appendix C - Role of Simulation in Dental Education

## C.1 Introduction

The overarching goal of dental institutions is to enhance teaching and learning and ultimately produce dental professionals that are responsive to the rapidly evolving external environment by delivering innovative, evidence-based education of very high quality using leading edge technology within a challenging supportive environment.

The digitisation of dental education is increasingly common. Digital technologies including CAD/CAM, 3D printing, Digital radiography and Dental Lasers have been around for a number of years and in the last few years, the use of virtual and augmented reality and haptics have started to be adopted by many schools, and evidence of their utility is increasing (Buchanan, 2001; Escobar-Castillejos et al., 2016; Towers, Field, Stokes, Maddock, & Martin, 2019). Much of the power of these technologies- particularly AR, VR and Haptics – lies in their ability to create or support or speed up the delivery of simulation as part of the pedagogical process.

Simulation is defined as a technique that aims to replace or amplify real experiences with guided experiences that produce or replicate substantial aspects of the real world in a fully interactive manner without going through the real situation (Gaba, 2004). Simulation in dentistry has a lot of benefits it provides the opportunity for students develop procedural skills and to practice safely before performing with real patients. It also has the ability to standardize and replicate procedures and to reduce consumable usage such as plastic teeth (S Perry, Burrow, Leung, & Bridges, 2017).

As a result, simulation is now a hot topic for dental schools across the globe, but there is a lack of clarity for dental educators on best practices and where the evidence may strongly advocate for one approach and where further research is required. To this end, I applied to the ADEE, and received, a scholarship which supported the hosting of a workshop at the University of Leeds. For this workshop, with support from my supervision team, I invited dental educators from across the world to attend and contribute their experiences and perspectives on the strengths and limitations of simulation technology as it stands today and share evidence-based practices.

The goal of this workshop was to use this meeting as a platform to develop a European consensus on the state of the art of simulation technology as applied to dental education. Delegates were asked to contribute to group discussions that would identify the state-of-art in simulation across five topics including: (i) the role of simulation in assessment of dental students; (ii) the pedagogy of holistic dental skill education; (iii) student perceptuomotor learning and decision-making; (iv) postgraduate and continuing education, and lastly (v) strategies for dental education to take advantage of immersive technologies.

Notes from this workshop were subsequently turned into prose by the delegates and I led the process of assimilating these into a coherent manuscript format. I then distributed this text to the wider research community and sought their input to ensure there were no gaps in our coverage. After consultation, I then integrated comments and edited the report to ensure coherence.

Whilst the final consensus report has involved several collaborators from across Europe and has developed extensively over the course of the 2 years since the workshop (stages detailed in **Error! Reference source not found.**), the text included in this chapter is the product of my coordination, assimilation and editing of collaborator comments prior to it being sent out for final approval from my co-authors.

**Table C-1** Consensus report on simulation in dental education timeline

| Stage | Timeline |
|---|---|
| ADEE Award to host workshop at Leeds | 2nd February 2017 |
| Hosted ADEE Workshop on “The Future of simulation in Dental Education” in Leeds | 27th April 2018 |
| Stage 1 - Working Groups to complete section themes | 23rd May 2018 |
| Stage 2 - Distribution of themes to wider community | 18th June 2018 |
| Stage 3 - Integration and Coherence | 6th July 2018 |
| Stage 4 - Consensus Report Validation | 11th January 2019 |
| Stage 5 - Consensus Report Approval | To be confirmed |
| Stage 6 - Publication | Summer 2020 |

## C.2 An International Consensus Report on Simulation Based Dental Education

In 1894, Oswald Fergus, with the help of one metal rod and two brass jaws, presented the world's first phantom head simulator to the dental community. His remarks made clear that the time for simulation in dentistry had arrived, because it was "rightly expected, that students should not be let loose to work their will on their suffering fellow creatures without first having acquired a proper efficiency" (Fugill, 2013; Suzanne Perry et al., 2015). 125 years later, simulation is now ubiquitous in dental education.

It is clear that we have come a long way from brass jaws and metal rods, but what evidence do we have for the efficacy of simulation? When and where should it be implemented in the curriculum, and what does the future hold for simulation in dental education? What is the evidence for improving patient safety, through effects on human factors especially of the later technologies? How much exposure to simulation is adequate? Simulation and it's revalidation? In April 2018, supported by the Association for Dental Education in Europe, thirty-one dental educators from across the UK and Europe met at the University of Leeds, England, to i) reflect on current best-practice in relation to dental education, ii) describe the benefits and challenges that simulation brings and iii) in light of the increasing prevalence of immersive technologies, discuss how dental education can benefit from simulation especially with its upcoming new digital revolution. Over the subsequent year, notes from the workshop discussions were shared globally with the wider educational community. Contributions ranged from healthcare specialists from disciplines with related challenges (surgeons performing minimally invasive procedures), psychologists working on the processes underlying learning, engineers pioneering the development of surgical technologies, and computer scientists working at the cutting edge of artificial intelligence. Contentious issues were debated and documented and in sum, 33 individuals from which 8 European countries, contributed to documents that have culminated in this consensus report.

In our workshop, five themes, identified by the organisers at the University of Leeds, were discussed. These covered:

(i) Role of simulation in the assessment of dental students

(ii) Pedagogy of holistic dental skill education

(iii) Student perceptuomotor learning and decision-making

(iv) Postgraduate and continuing education

(v) Strategies for dental education to take advantage of immersive technologies.

Within each theme, we considered the key issues and contemporaneous approaches, including how simulation might help and how simulation might hinder. These themes provide the structure for this report, detailing best practices, limitations in the evidence base and outlining outstanding research questions. These sections are prefaced by a definition of simulation and the report closes with recommendations for when and where simulation should be applied today.

### C.2.1 Simulation: A brief primer

Simulation has been effectively utilised for education, assessment, and maintenance of various skills across a diverse range of domains and has been particularly crucial in professions that demand a high degree of precision and safety – from the nuclear industry to health (Issenberg et al., 2005). The purpose of simulation is generally agreed to be to replicate or amplify real 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).

The earliest evidence of simulation efficacy in training came from the performance improvement of pilots in aviation training (Helmreich, 1997), which made flight simulation an integral part of the aviation industry to maintain high safety standards (Levine et al. 2013; Allerton 2010; Littlewood 2011). In the recent guidelines for Transforming and Scaling up Health Professionals' Education and Training, the World Health Organization strongly recommend the use of simulation methods with fidelity levels appropriate for various training/education contexts in health profession education. The guidelines also recommend 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).

Recently, Cheng and colleagues published 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). These guidelines aim to improve the quality of reporting of simulation-based research (SBR) by describing all the key elements of a research study. It will mainly benefit authors submitting manuscripts involving SBR, and assist editors and journal reviewers when assessing the suitability of simulation-based studies for publications. This comprehensive reporting will lead to advancement of the field of simulation in healthcare with editors, reviewers and readers able to critically appraise strength and weakness in an objective manner. The guidelines are necessary to guide the research efforts into systematic, unbiased, scientifically sound approaches for healthcare simulation research, which should provide a common language that recognises the value of research findings beyond any contextual differences.

### C.2.2 The role of simulation in the assessment of dental students

Our approach in the assessment of dental students should be holistic (realistic, reliable and valid) in nature. Assessment of dental students is not only throughout the dental course, assessment could even start as early as the entry level. How many students struggle with their manual dexterity? How can simulation help in assessing dental students to provide future support? These are all important questions that need to be answered.

Simulation training is playing a vital role in the assessment of dental students. The state of art for a simulation tool to assess dental students is thought to be a tool that can authentically reproduce a real-life situation, with real time variability decision making and realistic consequences to enable meaningful self-reflection and goal setting. It should support transferrable skills development, and wider community of peer learning and connect with evidence-based research and the ability to build a longitudinal record of tracking competence/transition development. Having said that, the technical approach via haptics and simulation training should not neglect patient consideration in this learning process as it is easy for a student to forget that there is a patient involved when using these technical approaches. The role of simulation in assessment of dental students is thought to have advantages and limitations as described in the table below.

**Table C-2** Advantages and limitations of simulation in assessment of dental students

| Advantages | Limitations |
|---|---|
| • Stimulates their personal learning – novelty and attraction for learning.<br>• Ability for further repetition to improve training.<br>• Deliberate practice.<br>• Enormous capacity to further training.<br>• Able to audit data.<br>• Transferable skills.<br>• Authenticity e.g. reproducing caries.<br>• Development of muscle memory / techniques.<br>• Allows training with low volume procedures and translational skills e.g. molar endo.<br>• Self directed learning- this includes student empowerment of learning | • Not complete simulation - 'safe environment' inability to feel e.g. soft tissues.<br>• Diagnostic development e.g. occlusal patterns and caries.<br>• Authenticity e.g. no fulcrum or adequate finger rest.<br>• Feedback from the procedure – is it too sensitive / educational aspect of to other simulation training which may lead the student to focus on improving other aspects.<br>• Not an immersive experience yet (not complete reductionist as it only focuses on a single task compared to real world situation of multiple skills in apparel such as working with a nurse etc reality). |

| | |
|---|---|
| process especially with digital feedback systems and also learning to self access.<br>• Evidence based / research-based simulation.<br>• Allows pear to peer review and comparison with objective feedback.<br>• Ensures objective assessment of tasks.<br>• Motivational- scoring objectively can lead to more motivation “gamification” however, focusing on one score can miss the purpose of learning and lead to maladjusted behaviours. | |

Currently there is active debate regarding simulation approaches used in the assessment of dental students. Assessment at the entry level is gaining interest and a recent study showed the potential of haptic virtual reality simulator by stratifying different levels of dental students performance across year groups (Mirghani et al. 2018), however, assessment throughout the dental training is thought to still need further development and should relate to multi-source evaluation as opposed to single spot tests. Further discussion around the scope, meaning, interpretation, and educational impact of simulation and assessment is also required. Development should benefit the evidence base and student perspective, and iterative development could be supported through potential feedback to staff and students to support learning and vice versa. Moreover, the skills could be maintained and re-visited if there isn't regular opportunities for real world practice.

Simulation is thought to have good potential in assessing dental students if the following is considered: first, focus needs to be on the learning process to support transition from novice through expert and support approaches that show skills translation from simulation to real patient care and on-going practice to support the latter. Second, personal development: (self-efficacy, resilience, reflection and goal setting). Third, skills development since simulation assessment can be very structured and objective: (practical, technical, non-passive decision-making process, transferability). Fourth, professional and inter-professional development. Finally, support research integrated educational and clinical approaches (Integrated clinical cases that follow the full patient journey). However, its ability in assessing dental students could hinder the following: lack of authenticity, – make authentic, based on research not opinion, false sense of skills & knowledge level, learning in isolation of real complexity and feedback, may drive wrong focus due to lack of mentoring and attention to numbers as well as focusing on parts of skills, rather than outcome of treatment, and this could lead to trivialisation of assessment e.g. aiming for technical perfection rather than skills adaptation to changing circumstances. This could be due to the lack of understanding of true impact, cost, profit pressures, company conflict of interest (in terms of tool capability or complexity), reproducing real-world complexity, interpretation of findings to produce meaningful change – variable stakeholder acceptance.  Moreover, there is a risk of there being the wrong. Overall, haptic simulation is likely to be of positive impact but further development would benefit the evidence-base and student perspective as well.

### C.2.3 The Pedagogy of holistic dental skill education

With respect to pedagogy, it would be considered good practice to transfer the teaching and learning techniques that are currently used to teach dental skills, to the simulation environment. These include techniques that address the imbalance between pre-clinical training and treating real patients. Haptics provide a great potential in this area, however, it is still not a substitute to the traditional simulators but a blended approach to teaching preclinical skills training. These learning techniques should employ a skills-based portfolio that centres around self-assessment reinforces a learner-centred curriculum throughout and encourages more critical reflection and peer review, mediated and recorded by a robust portfolio system. Self-assessment is a crucial skill for any professional but the value of unguided student self-assessment alone has been questioned (Eva et al. 2004; Davis et al. 2006). In addition, the accuracy of self-assessment may differ, as well as correlation between self-assessment and peer- and teacher assessments. In order for feedback to be useful it has to be clear and specific. The use of criteria is helpful but communication between individuals is not always without flaws. Recent studies suggest that VR-tools for teaching and assessment can provide more objective input and assist student self-reflection in the learning process (Garrett et al. 2015). These techniques should also develop 'core' clinical skills teaching and assessment in a much more overt way (such as cross-infection control, communication, posture, handwashing, medical emergencies, preparation of the clinical environment, working as a team, reflective practice, etc) before entry onto the clinics, in order to gate-keep access to patients and also includes vertical integration of clinical cases involving students across different stages. In term of technical approaches, the state of art would be models made by intra oral scanners importing into VR system, students can practice in VR before treating their patient. Intra oral scanning of real patient cases and transfer to the skills environment, either within VR or the wet lab, by 3-D printing also the use of 3D printed typodont teeth both in terms of laminar structure, and/or root canal anatomy. Haptic devices with 3-dof (dimensions of freedom) and 3D vision (Eve et al. 2014) can also play a role with consideration to the concept of ‘deliberate practice’, which is purposeful and systematic rather than just repetitive.

With the current teaching approaches there are some key points which need to be addressed. We know that the wide variety of teaching, learning and assessment practices, across Europe, both in relation to content and in relation to style, represent one of the main obstacles in the standardisation and quality assurance of dental education (Field et al. 2018). There are large discrepancies across Europe in terms of *what* is taught and assessed, and little consensus on recommended core texts and curricula at the clinical skills level. As an example of this, the philosophical approach to caries removal varies significantly across schools; How much caries do you remove?

From a clinical point of view, we are unsure about the cost-benefit equation in relation to buying into technical systems or indeed simply purchasing advanced typodont teeth. Little exists in the literature to show how students and staff receive advanced teeth compared to more traditional simpler typodonts. Simulation is now playing a major role in this aspect; however, the role of the tutor is debated - does simulation reduce the need for the tutor or increase the need (whilst allowing more students to practice more often, across a greater range of scenarios). One study investigated the effect of qualitatively different types of pedagogical feedback (FB) on the training, transfer and retention of basic manual dexterity dental skills using a virtual reality (VR) haptic dental simulator and found 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 (Al-Saud et al. 2017). Another study found students to be very welcoming towards a preparation validation tool but neither students nor teachers found that the tool reduced the subjective need for verbal teacher feedback (Kozarovska & Larsson 2018). This is in line with previous findings that students want to be seen and heard by a teacher (Baroffio et al. 2007).

Moreover, as it is always agreed that the students should practice until they reach a safe level to practice in patient but how much access students should be given to simulation is debated - should students be allowed to repeatedly practice the same exercise, or have a finite number of attempts, with a permanent record of operative activity that can be scrutinised? (Beilock et al. 2004) How real do simulation systems need to be? There are many articles that debate this topic from across a number of disciplines. See deliberate practice above (Wages et al. 2004; Mori et al. 2012). Many lessons have already been learned by the avionics industry in this respect, and there are many debates in this literature pool about the value of simulation, VR and augmented reality (Salas et al. 1998).

With regards to the role of simulation in the pedagogy in dental education, simulation might help to bridge the gap between pre-clinical training and treating real patients. Yet, this may be one of the important areas where simulation needs further developing. Although haptics provides a great number of advantages already and have the potential to be developed even further, it still is not, and may never fully become, a substitute for clinical skills training with real life patients.

The introduction of simulation to teaching should ideally be a gradual evolution, however many educators implement the use of simulation as a step change. It should be clearly thought out how simulation is involved purposefully within the intended learning cycle of the wider curriculum (Brownstein et al. 2015).

For an organisation, it is a big step to buy additional VR/haptics/simulation after that the implementation will be gradual, in parallel with trusted technology. As establishing and maintaining a simulation program may include staff training, curriculum integration and habit breaking which is even more challenging,

Some argue that VR/haptics/simulation is useful because we can standardise pathology or morphology and provide a consistent and uniform experience for all (de Boer et al. 2015), a safe learning environment, improved teaching resources, group learning - a shared resource / experience and self-learning. Variations in interfaculty grading is another challenge where VR/haptics/simulation may help in developing a consistent standard to which students compare themselves. Calibration of faculty improves the quality of teaching, grading and feedback. Software-based evaluation tools have been found to assist faculty calibration and act as an objective grading tool (Field & Vernazza 2013). On the other hand, simulation may have some limitations with regards to teaching. Issues include the ‘uncanny valley’ – proximity to ‘reality' might lead to unexpected outcomes (Mori et al. 2012) e.g. expectations that water should be misting up the mirror, can cloud judgement when it doesn’t happen. Is there tension between generality and bespoke (related to context e.g. dental schools / medical schools budget? Size of school, nature of collaboration, upgrade cycle)? Considering the dental staff will they engage with this new innovation? or find it challenging to traditional teaching practices. Other technology related limitations may include 3D vision (motion sickness), infection control issues – of technology and rapid aging of technology/computers.

### C.2.4 Student perceptuomotor learning and decision-making

Patient safety is of utmost concern with a worldwide attention focusing on the problem of medical errors and patient outcome. In recent years, a lot of emphasis has been directed on the issue of whether students should be learning on patients. There is an active debate on this point, there are external pressures on organisations to reduce the number of "never events" and to prove that students are safe at the point at when they enter the clinical environment. This is important for all stakeholders (students, staff, universities, patients, healthcare providers, regulators etc.). “Never first on a patient” is now the maxim in most countries, for example, in the UK “it is no longer acceptable or appropriate, for students at any level of training to practise new skills on patients, even if they have a patient’s explicit consent” (Aggarwal & Darzi, 2006).

Simulation practice can be valuable tool in increasing patient safety, as it can help with learning through protection and surgery rehearsals which subsequently increases the skills of students (Fried et al., 2005; Kneebone, 2009). Previously with traditional simulation, there may not have been sufficient evidence that students are prepared to begin to work safely on patients. At present, this decision is made on the basis of competency type assessments, and there is not yet a reliable way of tracking progress and development of clinical skills. Some students develop more slowly than others and this could also be accompanied with pressure from the curriculum to move forward to the next exercise whether all students have achieved a safe level to practice and unfortunately this is not always evident from traditional simulation. These are students who would benefit from immediate support rather than after a failed end of course assessment. Simulation may allow identification of these students at an earlier stage and initiate individualised education on surgical skills with students advancing at different rate (Personalised learning). Indeed, students who do not develop insufficiently can be redirected to other activities better suited to the skills they do have. Historically, there would have been limited opportunities to practice before entering the clinical environment, with VR/haptics/simulation the number of attempts at a particular procedure potentially is much greater (gamification may increase enjoyment and will lead to improve your score so may be motivational but may have issues as stated earlier), recognising that students learn at different rates and will develop skills to the point of competence at different rates. The implications of this are for improved patient safety provided that the simulation is authentic. There is now the potential to merge information from e.g. 3D scanning data within the virtual environment and predictably interact with that via haptic simulation. This allows surgery rehearsal and potentially improve student and patient confidence in the clinic.

Simulation can also help with decision making and have the potential in integrating a more complex environment. This could be due to simulation being limited in its interactivity in comparison to other existing platforms that offer artificial intelligence. Artificial intelligence could benefit students by taking history and complaint etc. There is current provision to enhance the experience with clinical decision making and treatment planning followed by clinical execution which is more aligned to a competency-based approach.

During the execution of treatment procedures, simulation may facilitate learners' ability to develop decision making, before and during a clinical performance as a result of new information. More complicated models could be developed that might allow a patient's disease to progress and decisions made at what point to intervene. Such models might also be used to demonstrate the effects of non-intervention together with the subsequent alternative and potentially more invasive treatments that would be required. Models were the patient ages from child to elderly with the disease progressing” life-cycle” of dental care approach, with the ability to alter risk levels and an element of artificial intelligence where the system can feed back to the student or escalate the complication level to assess competence level can also be considered, this would be educationally beneficial.

Simulation can also have a broader role at the expertise level. Simulation has a place at all levels of education from beginner to expert, but it can also extend to remedial training, revalidation, returning to work (e.g. for career breaks/health/accident) or equivalence assessment. It is important to make some distinction between the complexity of the simulation and the level of expertise present. A student who has no experience of handpiece skills would benefit from simple haptic tasks to develop dexterity, but this might be insufficiently challenging for the expert.

Simulation may also allow for a stage-based approach to skills develop, enabling the learner to focus on a narrow range of skills without distractors, which can be added in to gradually increase fidelity with the phantom head situation and then on to clinical practice. This might be particularly useful in the very early stages of a programme of study. Simulation also encourages self-reflection on performance compared to peers more easily than conventional phantom head.

There is greater standardisation of the learning environment and greater transparency on assessing the students compared to natural teeth or plastic teeth. Some plastic teeth vary significantly when they have artificial caries.

The adoption of these advanced simulation systems in learning will be gradual. Experience, research and success stories are needed to further develop and incorporate the potential of haptic simulation into dental training. Therefore, it is a gradual evolution and we must recognise that there will be differences in adoption of technologies. For the foreseeable future, a blended learning environment and traditional phantom head training will be necessary to bridge the gap between pre-clinic and clinical training. Our current model blends a variety of online resources pre-class to maximise staff student time and contact on actual physical activity rather than didactic teaching. Integrating this with haptics and immersive simulation would seem a reasonable approach (at least blended for present but eventually technology emersion will occur, possibly with more robotic dentistry also occurring). Lastly, consideration should be given for the potential that too much reliance is placed on simulation, in addition they may learn behaviours/skills that have to then be unlearnt when entering the clinical environment. Some issues in implementing these technologies may include: The need for more evidence that simulation is of benefit in improving outcome (student competence), Lack of collaboration and sharing of experiences with these technologies between institutions and manufacturers, Costs/added value (it is difficult to get started due to the considerable initial capital outlay, and funding stakeholders often ask to the evidence that it is worth it, the belief that simulation is not realistic – but does it have to be?), availability of training courses for the skill set that is being addressed and getting technology skilled teachers as they are frequently the people who hold back the move forward.

### C.2.5 Postgraduate and continuing education

Postgraduate and continuing education are very important in developing the skills of practitioners to remain fit to practice and improving patient safety and care. It is also important to identify the type/level of expertise of dentists (the level of expertise of dentist seeking postgraduate and continuing education varies, they could be a recently graduated dentist, practising dentist, dentist in specialisation fields or out of practice returning dentist) who benefit from this education, what are their struggles, how to fulfil their needs and how to develop it?

Simulation in postgraduate and continuing education can help in different ways such as; developing new skills and revisiting areas of forgotten skills. Practicing dentists including recently graduated dentists and out-of-practice returning dentists might all benefit from it. Designing scenarios and access to training facilities that suit the level of expertise of the dentist and ability to cover multiple scenarios and complexity (implant, periodontal surgery, etc.), remedial management and adjunctive procedures "mopping up" considering dentists in practice and in specialisation fields. Furthermore Rehearse "real patients" - scanned data into digital/haptic environment.

The state of art would be an education or technology that serves in filling the gaps in postgraduate education, fields of specialisation, out of practice returning dentists and helps in setting international standards. Provides immersive experience – simulation of soft and hard tissue (gradient of resistance) – considering the patient as a whole. As well as identification of the level of realism needed.

With the current approaches, there is limited resources to practice multiple scenarios before live patients – ability to simulate the clinical situation, not just phantom head but also there are limited availability of courses, CPD courses designed for those who had time away from practice/ struggling dentists/normal verified CPD (self-reflection). Some engagement with Deaneries and possible provision of "haptic" simulation has been considered but it still lacks evidence due to minimal publications in this area. CPD and revalidation assessment, in some countries, medical practitioners are subject to revalidation to prove their skills are up to date and they remain fit to practice. It is intended to reassure patients, employers and other professionals and to contribute to improving patient care and safety.

The principle of adopting simulation in postgraduate and continuing education is a step change however its application to different fields is a gradual evolution. Extensive research in this area is needed and consideration should be given to the area of usage such as if used for validation – dentists may "game" the situation. Isolation from real life and clinical (live patient) experience, absence of communication skills and maintenance – cost – purchase and indirect costs and dependence on technology, mind-set, and fear of technology could act as an obstacle in this field.

### C.2.6 Strategies for dental education to take advantage of immersive technologies

The majority of schools already have dedicated a phantom head laboratory with enough units to teach large groups of students which can be adapted to simulate a large number of procedures from basic impression taking, periodontal treatments, caries removal and oral surgery through to complex restorative work. Where available, and permitted, real teeth can also be used in phantom heads although this is becoming increasingly difficult due to issues with cross infection control, consent and cost of clinical waste removal. However, with advances in 3D printing and materials, it is becoming easier to simulate biological tissues and caries with 3D printed carious lesions providing a standardised realistic model to develop both the motor skills and decision-making processes involved with caries removal and cavity design. 3D printing from digital scans and CT scans can allow anatomically realistic models to be created which are already used for training in other specialities and are now being developed in dentistry (Werz et al. 2018; Kröger et al. 2017). Furthermore, the physical presence of the head, chair and unit allow for ergonomic training, moving about the patient and working with an assistant. However, phantom heads produce a large amount of plastic waste from the use of typodonts, which is not ideal in terms of financial or environmental sustainability. There is also a limitation in the materials as typodonts are often not as hard as real enamel, and models such as those used for periodontology or oral surgery procedures are often not hugely realistic in reproducing the soft tissues. This can lead to procedures appearing much harder or easier than they are on real patients.

Currently the standard education tool in preclinical level is the use of phantom heads in combination with the use of plastic typodonts, and on occasion real teeth. In order to assess where haptics fits into the future of dental education, and why or how it should be integrated into the curriculum, it is important to look at the pros and cons of current practice. We must also evaluate the characteristics of haptic trainers and identify areas where haptics may be able to offer a better alternative or adjunct to that which is currently available.

The use of phantom heads alone, as with any educational resource, is only of benefit with supportive educational material and supervision. The heads work best as a training aid when tutors are present to give feedback, although this feedback is subjective. Various strategies have been developed to overcome this subjective nature, such as the use of marking criteria (Huth et al. 2017), calibration exercises and even use of digital technology (Kateeb et al. 2017; Wolgin et al. 2018). Although this is listed here as a negative it could also be seen as a positive, as most schools already have the infrastructure and staffing in place to provide the necessary support to fully utilise phantom heads.

Virtual reality simulators (with and without haptic technology) have been increasingly adopted across many dental schools around the world. Additionally, 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. Despite that, they are still considered in their early stages in terms of development, design features, applications and utility. In summary haptics have a role to play in dental education but the current limitations must be recognised, with their use tailored to utilise their strengths. There needs to be managing the expectations of educators so they do not expect a complete training solution for every clinical scenario and every student, but do see it as a useful adjunct to the armoury of preclinical training simulation options currently available.

Haptic machines are usually more portable than phantom heads and can be set up in nearly any room without the need for water, compressed air or waste facilities. This is an advantage in many universities, where cohort numbers are increasing and space is at a premium. Following on from this, and alluded to previously, haptic machines do not produce waste plastics or materials. Large numbers of procedures can be repeated unlimited times and can be “rewound” to particular key steps in the process where extra practice is needed without using up large numbers of plastic teeth or repeating the whole exercise. Whether running costs overall are cheaper than phantom heads is hard to assess as the fast processing computers needed for some VR programmes can use large amounts of electricity and literature on comparative running costs could not be found.

The realism of the haptics, in terms of sensory feedback of the different tissues, is probably currently comparable to phantom heads rather than real tissue, although it is accepted improving technology may increase realism in the future for both phantom head and haptic systems. As with phantom head, many systems do not currently have the correct “stiffness” in their haptic feedback to portray the various dental tissues accurately (Wang et al. 2016).

Haptics can give immediate quantitative feedback after a procedure is completed, as well as further analytics and visual comparisons to “ideal” preparations. This feedback is individualised to the learner however**,** students routinely report that they want not only feedback about their work but advice on corrective measures, therefore as with phantom heads, haptics are not best utilised as standalone training for learning completely new skills and trained tutors are required to interpret the feedback and give corrective advice. Although it has been shown haptics can be used to acquire new motor skill this is best when used in combination with a tutor to provide feedback and not just the digital analytic feedback (Al-Saud et al. 2016). The training of staff to be confident with the use of haptics is another consideration in their implementation.

The number of procedures that can be practiced on any one haptic are generally limited compared to a phantom head. This is because of the limitations of the VR and limited content and software available. Although, if all the currently available haptic systems are taken into account as a whole, a large number of procedures can be simulated on the different machines (Wang et al. 2016). Although some simulators do include finger rests these are not yet comparable to a clinical scenario (Wang et al. 2016). This may be a disadvantage if there is the potential to learn incorrect use of finger rests or not develop them in the preclinical environment. The haptics also do not allow the development of team working skills- working with an assistant, four-handed dentistry.

It would seem the strengths of haptics lie in providing immediate quantitative feedback and allowing repetition of steps in a procedure a number of times without producing waste or requiring repetition of the whole procedure. This stepwise approach to training – breaking a procedure down into key steps and practicing each individually is a recognised technique in surgery (atomisation, or deliberate practice). Although expensive in clinical practice, it works well but is hard to recreate in the dental environment, as in surgery the operation is often completed in pairs of senior and junior surgeons who can complete individual steps, but in dentistry, the trainee works alone. Therefore, in this case, haptics offers an advantage over phantom head or real clinical practice. Haptics may also offer an advantage in the practice of procedures that are less frequently encountered or socially less acceptable to practice on patients or students. Examples may be more complex restorative work, crowns, bridges or implants.

Haptics does not appear to offer an advantage for the practice of techniques and procedures such as impression taking, or working with an assistant, all of which can be practiced more on traditional phantom heads. It would make sense therefore when developing educational strategies to focus on the strengths of haptic trainers but also work towards how we can address the challenges and barriers currently limiting the use of haptics.

### C.2.7 Three suggested strategies to implement Haptic simulation

(1) In Millers' Triangle (Miller 1990) for the development and assessment of clinical skills, phantom head and simulation work is usually placed in the "shows how" level, second from the top below the "does" level. Feasibly for haptics to be used in the same way enough machines would have to be acquired by each school for group teaching sessions of new skills for all levels of students. There have been suggestions however that the triangle include a further level at the top consisting of "does well", that is further training to become not just safe but expert (Beard 2008). Therefore for schools which have taken the first step in to haptic technology and purchased a small number machines, a sensible strategy may be to use it for pre-surgical treatment planning and practice. This use certainly aligns more with the current use of haptic trainers in other specialties, such as surgery or aviation, where haptics are used by qualified doctors and pilots who are not learning completely new skills, but rather are using haptics to expand and consolidate existing skills (Grantcharov et al. 2004). Mindful of the advances in digital dentistry, and how these can be used to support training, students could upload intraoral scans or study model scans to the haptic machines to practice a procedure, or difficult part of a procedure, on a particular patient in advance. The benefits of pre-surgical planning using 3D models is well documented already in surgery (Hangge et al. 2018; Marro et al. 2016; Pucci et

al. 2017) and this approach also overcomes the comparable lack of varied content available in many machines and the lack of machines for all students. Furthermore, the haptic machine can provide objective quantitative analytics helping students identify areas for improvement. This use would mostly benefit students in higher years who have already developed some self-assessment skills and would be less dependent on a tutor for corrective advice. Again, this strategy aligns more with theories such as the 10,000 hours of deliberate practice to develop expert skills and consolidate good practice rather than learning something completely new. This strategy should also be easier to implement with a limited number of machines and is a clear example of where the use of haptics is superior to current practice.

(2) In order for any strategy to be successful, the haptic industry needs to be included in discussions to develop mutually supportive approaches to integration. Currently only a gradual evolution is possible but in order to have a step change a shift in accessibility, user friendliness and integration with current and developing technologies is needed. A possible analogy here is the impact of the iphone on the use of smartphones. By developing a user-friendly interface; and making the development software open source so that anyone could create content; along with the nature of phone ownership being through monthly payments and easy upgrade of technology as new models arrive, this encouraged users to adopt a new expensive technology without worrying about it becoming obsolete or unusable. The content available grew quickly, often with apps offering free sample content with payment required to then get access to the full content, and apps were reviewed which led to a form of self-regulation and good content being easy to find. Perhaps the manufacturers of haptic machines could adopt some or all aspects of this approach. Whilst not in itself an

educational strategy it does address the often ignored but unavoidable obvious problem, which is the apprehension, cost and feasibility of schools adopting an expensive and fast evolving technology with relatively little evidence base to support its superiority over current practice, and therefore being one of the main barriers to the use of haptic technology.

(3) Once haptics are available in larger numbers with associated varied content industry must then help facilitate multicentre trials and utilise the big data and analytics generated by increased use of the machines. Further areas where it has been identified more research is required are the fidelity of the multisensory feedback, the ergonomics of the training platform and the effectiveness of evaluation methods (Wang et al. 2016). This will allow sufficient data to assess educational strategies, identify successful approaches, comparisons with current models and further development of haptic use.

### C.2.8 When should simulation be used?

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). Although the majority of simulators in health care education are designed for learning of procedural skills (e.g. 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). Nowadays 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).

### C.2.9 Where should simulation be used?

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 understanding of basic principles of motor skill acquisition. Beyond perceptuomotor 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 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 (Mason 2005).

### C.2.10 Conclusion

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 various types of dental simulators (mostly traditional phantom head, in addition to augmented and virtual reality based simulators).

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. This would facilitate the formulation of best practices recommendations for the use of dental simulators especially virtual reality simulators. The inherently broad and multifaceted nature of the topic demands collaborative research efforts from various disciplines including dentistry, education, engineering, cognitive psychology, and computer sciences.